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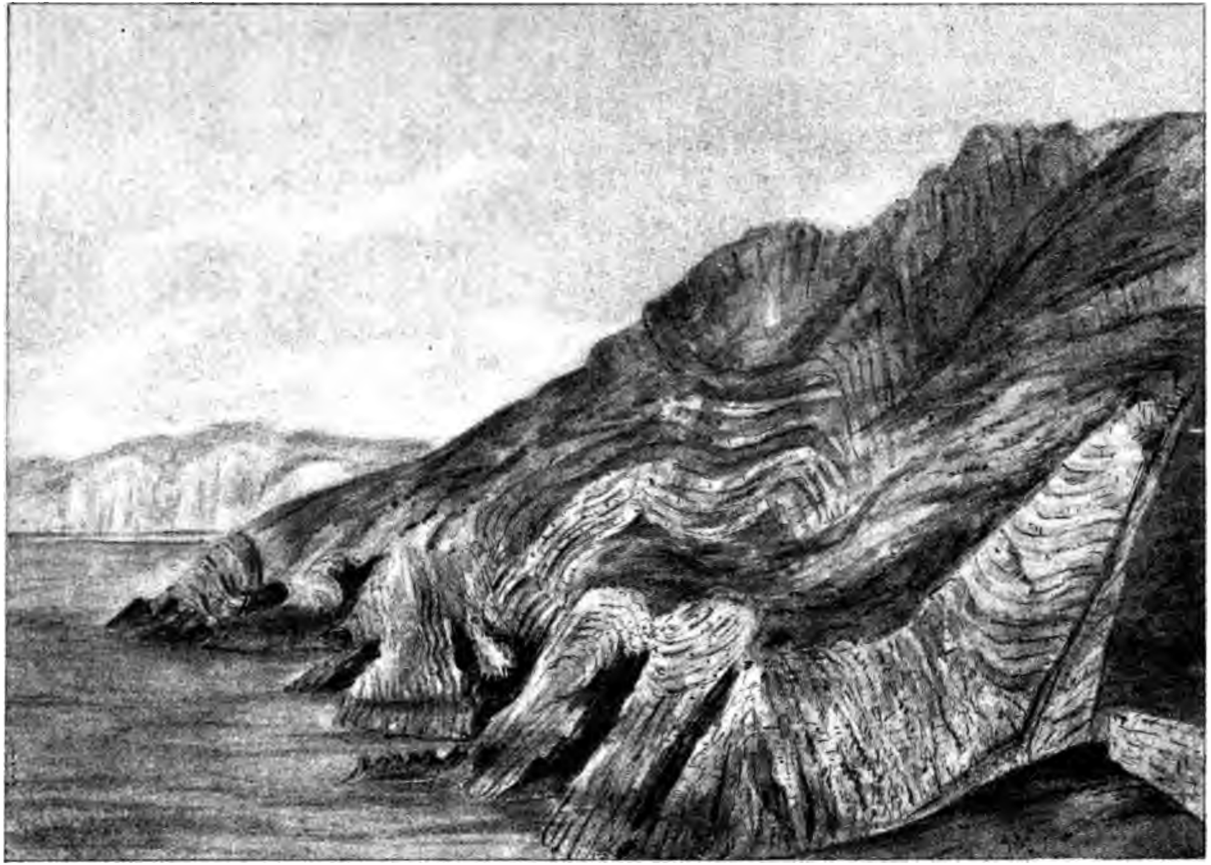

MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

INK-PHOTO. SPRAGUE & Cº LONDON

CRYSTALLINE SCHISTS HOLYHEAD.

THE ORIGIN

OF

MOUNTAIN RANGES

CONSIDERED

EXPERIMENTALLY, STRUCTURALLY, DYNAMICALLY,

AND IN RELATION TO THEIR

GEOLOGICAL HISTORY.

BY

T. MELLARD READE, C.E., F.G.S., F.R.I.B.A.,
PAST PRESIDENT OF THE LIVERPOOL GEOLOGICAL SOCIETY.

LONDON:
TAYLOR AND FRANCIS, RED LION COURT, FLEET STREET.
1886.
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PREFACE.

THE Origin of Mountain-Ranges is a problem that has interested geologists ever since the structure of the crust of the Earth has been systematically studied. Notwithstanding this, I know of no work in the English language devoted entirely to a consideration of this important subject, or containing what may be considered a systematic theory of mountain-building. The line of geological thought in this country has hitherto run more in stratigraphical than dynamical grooves. The American geologists, forced into contact with the stupendous mechanical problems presented by the geology of their continent and great mountain-ranges, have devoted considerable practical attention to dynamical geology. Still, scattered through the works of the great masters of geology who have flourished in our own country are to be found the germs of most true geological reasoning, dynamical and otherwise.

An attempt such as mine to provide a systematic treatise will probably be considered an ambitious one. Whether the theory here presented to the geological world be the true one or not will hardly be determined by such a consideration. The true test, as of everything geological, is *time*; and if it be found that the views here set forth best explain the manifold aspects of Nature, and otherwise meet the conditions of the problem, the ideas will live; if not, they may still survive as partial truths.

In the mean time I have thought that the presentation of the subject in as complete and practical a form as is possible to me at the present time would have its value, and this must partly be my excuse for publishing.

Throughout the book I have attempted to do justice, by means of extracts and notes and references, to previous workers in the same field. This is perhaps the most difficult duty of a scientific author; and if in this particular I have failed, as I feel that I must have done in many cases, I trust it will be attributed to nothing more than inadvertence.

Such are the rapid strides with which our favourite study advances that, although the writing of this work has been continuous, I have constantly had to refer in footnotes to important work done, even since the type has been set up.

The subject is in many respects difficult and even abstruse. To render the information more readily available, and to enable the reader to grasp the ideas in the concrete, I have taken some pains to illustrate the text. The sketches of scenery have in every case been drawn from Nature, and generally during my holiday rambles. The shaded views are ink-photos of sepia-drawings prepared by me from the original sketches. The line-drawings, both of scenery and structure, are photo-lithographs from drawings I have specially prepared for this work, and also are in all cases from Nature. Some of the illustrations, as will be seen by the descriptions, are reproductions from reports published by the United States Geological Survey and the Second Geological Survey of Pennsylvania; the remainder of the diagrams and maps are mostly from my own drawings.

It now becomes my pleasant duty to thank those who have, during the progress of the work, afforded me aid and sympathy. To Prof. Powell, Mr. M'Gee, Prof. Lesley, and the Governments they represent, my best thanks are due for the presentation of various important reports on the Geology of the United States, and for permission to use the maps and sections. From the Liverpool Free Public Library Committee, and Mr. Cowell, their librarian, I have received important help through the loan of valuable works of reference, and even to the extent of their adding to the Library at my suggestion. With thanks to these gentlemen and numerous kind friends, I conclude, for the present, work which, though arduous, has at the same time been as pleasant as it was engrossing.

T. MELLARD READE.

Park Corner, Blundellsands,
Liverpool,
Sept. 30th, 1886.

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THE

ORIGIN OF MOUNTAIN-RANGES.

CHAPTER I.

VARIABILITY IN THE TEMPERATURE OF THE CRUST OF THE EARTH, AND ITS CAUSE.

IT has been long known that, as the crust of the Earth is penetrated, the temperature increases with the depth. Attempts have been made to educe a uniform rate of increase from the varied observations that have been made, but hitherto, I think, with no great amount of success. The temperature, we may say, universally increases with the depth, whether it be below the frozen soil of Siberia or in the regions of the torrid zone; but the rate of increase is inconstant, even taking into account the varying degrees of conductibility of the rocks penetrated.

It appears to be inconstant even in the same bore-hole; and in places not far apart the rate of increase varies considerably. Thus the rate of increase at Astley Pit, Duckinfield, Cheshire, was, on the average, 1° for every 83·2 feet for a depth of 685 yards; while similar experiments at Rose Bridge Collieries, Ince, near Wigan, for a depth of 815 yards, gave an average increase of 1° in every 54·3 feet*. In some of the Paris artesian wells the increase was found to be 1° for every 50 to 60 feet; while the great well of La Chapelle, at Paris, showed, to a depth of 600 metres, an average increase of 1° in 94·3 feet†. In experiments made at Przibram, in Bohemia, by Herr Johann Grimm, Director of the School of Mines, in a depth of 1900 feet there was an increase of 1° in every 135 feet. The experiments at the Mont Cenis Tunnel show an increase of 1° in 93 feet, without correction for the convexity of the ground.

The deepest artesian well in the world is one at Pesth, which had reached 951 metres when last reported upon, and yielded water at a temperature of 161° F. Unless we know the depth of the stratum from which this water was derived, it would be impossible to arrive at the rate of increase; but if this temperature was that of the rocks not much lower than the bottom of the bore, the increase would be as much as 1° for every 30 feet.

Professor Lebour, in reviewing the present state of our knowledge of underground temperature, gives a table of observed increases of temperature in various localities, 57 in all, in which the range is from 28·1 feet in Anzin, in the north of France, to 157·2 feet in the Minas Geraës Mines in Brazil, for every degree Fahrenheit.

Allowing for all the difficulties which beset observations of this character, I think it will be conceded that the range of increase varies very considerably in different localities and areas of the Earth's crust. That these existing variations have been constant in time throughout these areas would scarcely be maintained by any one. If not, it follows that fluctuations of temperature occur in the solid crust of the Earth. That the rates of increase of heat vary during geological time for various localities would seem an obvious truth, even leaving out of account those greater revolutions of the Earth's surface by which seas have become lands and lands seas.

---

* British Association Report on Underground Temperature, 1870, pp 31, 32.

† Ibid. 1873, p. 253.

Accepting as an inference of high probability that the increase of heat, whatever the rate, progresses downwards until the temperature of molten matter—or matter that would be molten if freed from the superincumbent pressure—is reached, so enormous a reservoir of heat lies below, that it would seem puerile to doubt that the extremely thin cooled crust must respond to internal changes of temperature that in all probability take place in the enormous mass of heated interior rock.

But it is unnecessary to rest this thesis on surmise and supposition. Volcanic activity shows that such redistribution and changes in the heat of the interior as the solid crust is approached are constantly, if with extreme slowness, taking place. Even if we concede Mallet's view, which I am by no means prepared to do, that volcanic heat is a secondary product, a conversion of the mechanical energy of a collapsing crust, the fluctuation of heat in the outer envelope is admitted, if accounted for in another way. It is, however, rather unfortunate for the theory that, in the actual investigation of the structure of mountains, no one has yet been able to trace any apparent connexion between the pressure to which the rocks have been subjected and the volcanic activity accompanying mountain-building.

For instance, the enormous forces which have (as so clearly shown by Dr. Callaway, Professor Lapworth, and the officers of the Geological Survey *) folded the strata of the Northern Highlands in such a way as to superimpose Archæan Gneiss upon Silurian rocks, so as to deceive even the practised eye

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* "The Newer Gneissic Rocks of the Northern Highlands," Dr. Callaway, Q. J. G. S. 1883, pp. 355–422. "The Secret of the Highlands," Prof. Lapworth, Geol. Mag. 1883, pp. 120, 194, 337. "The Crystalline

of a Murchison as to their succession, have not developed heat sufficient to melt any of the beds in question. Enormous ruptures of the strata have taken place, beds being driven over beds for miles; rocks have been ground to powder, yet none of them, so far as we know, have been thereby fused. Volcanic activity accompanies these terrific but slow displays of force, as we shall see as the subject develops itself. But no direct connexion between the pressure and fusion has yet been pointed out. In all cases the molten rock has welled up from great depths below the compressed materials of the mountain range. In other cases we find great displays of volcanic activity, such as Professor Judd so graphically describes in the basal wrecks of volcanic cones in the islands of Mull and Skye *, unaccompanied with anything like the amount of folding, pressure, and contortion that we find in the rocks of the Northern Highlands.

And here it may be as well to point out that the amount of lateral compression or shortening of the strata at the *surface* must, on the theory of a collapsing crust, be a measure of the mechanical energy which has been developed. Hence it follows, that if the volcanoes of Mull and Skye were due to tangential strains accumulating in those localities, the enormously greater strains to which the Archæan and Silurian rocks of the Highlands were subjected should have reduced most of these rocks to a state of fusion. This the pressure has not done; therefore we must seek another explanation of volcanic activity.

But in Mr. Mallet's ingenious theory there lies another difficulty, of a sort we can contemplate without appealing to geology. It is evident that a collapsing crust cannot develop

---

Rocks of the Scottish Highlands," by Dr. A. Geikie and Messrs. Peach and Horne, 'Nature,' Nov. 13, 1884, pp. 29–35. "The Geology of Durness and Eriboll," by B. N. Peach and J. Horne, British Association Report, 1885.

* "The Secondary Rocks of Scotland," Q. J. G. S. 1878, pp. 660–743.

more heat than is due to the distance it falls through; hence, taking the crust as a whole and supposing the entire mechanical effect to be converted into heat, for every contraction of the radius of the Earth of 772 feet only sufficient heat would be generated to raise the mass of the falling crust 5° Fahr. It is true, if the total heat were concentrated on certain limited points or lines, the point of fusion would be reached; but it appears to me that, in the enormous period required for a shortening of the Earth's radius by 772 feet, the whole of the secondary heat derived in this way would be dispersed into space. If, in addition to this, we consider how much of the mechanical energy would be dissipated in other work than that of heat-producing, we may form a conception, without appeal to mathematics, of the utter inadequacy of such derivative heat to account for the enormous volcanic activities which geology shows us have been developed during the history of the Earth.

If, on the other hand, we assume, as we have fair grounds to do, that at a depth of about 30 miles the interior of the Earth reaches a temperature sufficient to melt rock (if it were at the surface), say 3000°, we find that this heated inner spheroid to the crust above bears the proportion of about 43 to 1.

It does not enter into the scope of this work to speculate upon the *cause* of this internal heat. Its existence is accepted, and that it is subject to local fluctuations seems a reasonable supposition. Even if we admit that the Earth is solid from the circumference to the core, considering the multifarious materials and elements of which it is composed—judging by the crust—slow chemical interchanges, accompanied by increase or decrease of heat, must have been taking place during past geological time.

Unless we accept Mallet's theory in its entirety, volcanic activity cannot but be due to fluctuating and differential heating of the layers of heated rock lying immediately below the cooler crust. That this heated matter responds to changes slowly taking place on the crust itself it will be my object to show.

So many and great have been the difficulties connected with the contractional hypothesis, that several eminent geologists and physicists have assumed that a layer of molten matter lies between the solid outer shell and a solid inner spheroid. In this molten cushion is sought the flexibility supposed to be necessary to account for the plications and foldings which, more than crushings, we find in the solid crust. While a collapsing solid shell, floating on a more or less evenly distributed intercalated zone of molten rock, is hypothetically postulated by many geologists, and among others by no less an authority than Professor Prestwich *, Mr. Osmund Fisher †, following out the theory to its logical conclusions, supports his mountain-ranges by floatation in a similar zone of heavier matter.

Speculations such as these, if we keep in view their hypothetical nature, are perfectly legitimate. What we cannot ascertain by direct experiment we desire to reason upon in another way. Some eminent astronomers and physicists tell us, however, that the Earth is as rigid as steel, or at least glass, from the surface to the centre ‡; and Professor Dana says, "Moreover I am led by the conflicting views of the best authorities with regard to the condition of the Earth's interior to hold very loosely to any theory of mountain-making. We wait for the physicists who believe in a solid Earth to give us a theory which will have in view all the geological facts" §.

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* 'Geology, Chemical and Physical,' p. 216.

† 'Physics of the Earth's Crust,' pp. 146, 147. Archdeacon Pratt is quoted in support of this view.

‡ See Sir Wm. Thomson, British Assoc. Rep. 1876, and G. H. Darwin, Phil. Trans. 1879, part 1.

§ American Journal of Science, April 1885, p. 337, no. 172, vol. xxix.

That there is no incompatibility between the assumption of a solid spheroid and the known facts of geology I have, approaching the question by an independent line of investigation, satisfied myself. Nay, I am prepared to go a step further, and to maintain that such an hypothesis best satisfies all the conditions of the phenomena of our globe looked at from a geological standpoint.

If we assume a solid heated interior, the solidity must be due to the pressure of superincumbent matter. If by any changes in the crust this pressure should be sufficiently relieved, it will follow that the heated matter will assume the molten form. Here, at present, I must break off, leaving the further explanation to grow out of the investigations of the facts of Geology to be recorded in future chapters.

CHAPTER II.

EFFECTS OF DIFFERENTIAL HEATING ON THE EARTH'S CRUST.

LEAVING for a time the question of the solidity of our planet, let us consider what effect a local change of temperature would have on the Earth's crust. For the sake of the argument, I will ask the reader to grant me the fluctuations of temperature required. That such fluctuations really take place again and again will become clearer as we proceed. Progress is, however, only obtained by steps, and I do not seek a final assent to any proposition until the whole line of reasoning is laid bare.

The average rate of increase of heat deducible from the 57 examples given by Prof. Lebour is 1° Fahr. per 64·28 feet of descent. Professor Everett thinks 1° per 56 feet nearer the mean.

Professor Prestwich, by an elaborate series of calculations and corrections, arrives at from 45 to 50 feet as the mean increase of temperature for the whole globe*.

Whether the observed rates of increase from the several localities in Prof. Lebour's schedule would be maintained at the same rates at greater depths can only be a matter of surmise. The rate may either increase or decrease. The observations are necessarily so limited in range of depth, and so liable to error, that it has been impossible to establish either one proposition or the other. For the sake of this inquiry we will take an increase 1° Fahr. per 60 feet and a mean of 50° temperature at the surface. At this rate the temperature of 3000° Fahr. would be reached at a depth of 33½ miles. The temperature of lava, as it issues from Vesuvius, is not less than 2000° Fahr.*, and probably much more. If we therefore assume 30 miles thickness of crust, the surface-temperature being 50°, and the base shading off into rock approaching the melting-point, we shall probably not form a very incorrect notion of what actually exists. But from the observations recorded we may fairly and legitimately assume also that this potentially melted rock does not lie everywhere at the same depth below the surface. At some places it may be much deeper, at others considerably less. It seems to me straining at a harmony that does not exist in nature to exclude the evidence of observations ranging considerably on either side of this assumed mean, and attributing the difference to errors incidental to the mode in which the observations were made.

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* 'Chemical and Physical Geology,' p. 414.

Let us further assume that in one area of the globe the temperature-plane of 3000° Fahr. was in times past situated at a depth of 35 miles, and that by internal changes it gradually rose to within 25 miles of the surface †. Discarding for the moment the effect on the lower 10 miles of rocky matter, what influence would the change have upon the upper 25 miles of crust? It would be this: the strata at 25 miles deep would be raised in temperature 857°. The mean temperature of the surface would remain that due to the latitude and local conditions, or at all events only change to the extent that the climate had changed during the time that had elapsed. The intermediate zones of rock would be raised in temperature in proportion to the depth; the mean increase for the whole 25 miles being 428°·5. But the rock cannot change in temperature without also changing in volume.

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* A. Geikie, 'Text-book of Geology,' p. 227.

† The surface temperature, for the sake of simplicity, is assumed to be zero.

According to a series of experiments I have myself made on various kinds of rock, I estimate the mean linear expansion of rocks composing the Earth's crust at 2·77 feet per mile for every 100° Fahr. Assuming that this holds good throughout the range of temperature of the whole 25 miles of rocky crust, the mean expansion of every component cubic mile so affected would be 11·869 feet on every side of the cube. That is, the linear dimensions of the cubic mile would increase $\frac{1}{445}$, and its volume $\frac{1}{148}$, so that every 148 cubic miles of original matter would become 149 cubic miles. If the area of the Earth's crust so affected measured 500 miles by 500 miles, the crust 25 miles thick heated to a mean of 428°·5 Fahr. would increase in volume to the extent of 42,230 cubic miles.

These figures will at first sight no doubt look well-nigh incredible, but it is a simple calculation that any one can test for himself.

We must now ask ourselves what would take place from this enormous increase of volume in the solid crust.

In nature the form of the mass acted upon by such a change of temperature would most likely be lenticular, but this would not affect the argument, as the 500 × 500 × 25 miles must be taken as representative of the volume of the crust of the earth so affected, whatever its form.

It is evident, on very little consideration, that this mass of rock cannot expand laterally, for in that case it would displace the crust of the earth surrounding the affected area; nor downwards, for that would displace the solid foundations of the Earth itself. It is only free to expand upwards. We may therefore take it that the lateral increase of volume will be transformed into an upward one. The lower strata would expand the most, the surface would not expand at all. The behaviour of the crust under these conditions would depend on the nature of the strata affected. If the beds were comparatively thin, they would become folded and packed together in a more or less vertical position. The internal strain would have the most effect in the region of greatest expansion, and the packing of the strata in this locus would ridge up the surface and burst it along the lines of greatest weakness, for the surface layers would be unaffected by the subterranean heat.

The foregoing is but a crude illustration for the purpose of conveying to the reader some of the elementary and fundamental principles upon which this inquiry into mountain-building is based. In the following chapter I shall detail some of the experiments I have made, with the view of establishing additional facts necessary for the construction and development of the theory.

CHAPTER III.

MECHANICAL EFFECTS OF EXPANSION BY HEAT ON VARIOUS MATERIALS, AS KNOWN THROUGH COMMON EXPERIENCE.

Probably no one is unaware of the fact that if hot water is suddenly poured into a glass or porcelain vessel, it is very likely to crack. This is due to internal strains developed through the expansion of the inside of the vessel, while the exterior rigidly retains the original dimensions.

It is, however, perhaps only known to a few that a vessel formed of a more ductile material, such as lead, if repeatedly heated and cooled, permanently increases in size with every such operation.

It is evident from these two simple examples that the effect of expansion by heat is governed largely by the nature of the materials acted upon. Any practical man who has had experience of the setting of boilers, the building of chimneys, or the erection of kilns, knows that the effect of such heat as they are subjected to is very destructive of the structure. It arises from two causes: first, the unequal expansion of the heated interior compared with the cooler exterior; and, second, the low tensile strength of brick-work. The heated interior brick-work expanding ruptures the exterior, which expands less. This effect does not follow from one operation, but through repeated heatings and coolings. At every heating the brickwork is moved, but in a way imperceptible to the eye, and it does not recover its original dimensions on cooling. The accumulated results of these internal movements soon, however, become sensible by rifts in the brickwork. To counteract these destructive forces, it is usual to bind the brickwork together with iron rods or hoops, which, having a high tensile strength, hold the work more firmly together *.

Engineers know that the effect of expansion in metal-work has to be carefully guarded against by arranging the materials in such a way that they can have free play. For instance, a line of hot-water pipes for heating a building requires, even though never rising above a temperature of 212° Fahr., considerable play, and has to be fitted in places with what are called expansion-joints, otherwise the pipes would fracture or the ordinary joints leak. The great iron tubes across the Menai Straits rest upon rollers, or they would tear the structure to pieces even by the variations of atmospheric temperature.

Mr. Jas. Mansergh, M.I.C.E., describes in the 'Engineer' (Nov. 14th, 1884, p. 378) a remarkable and curious instance of the expansion of railway metals through the heat of the sun:—

"Rails known as Barlow's rails, 11 to 12 inches broad at the base, forming their own sleepers, were temporarily laid across an embankment, being firmly 'fished up' or bolted together with saddle-pieces on the underside of the rail, the

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* "Herr Eckhartz has expressed his opinion that the cause of crevices being formed in chimneys is the difference of temperature between the inner and outer surfaces. While in many cases in an ordinary factory chimney the mantle has internally a temperature of nearly 600° Fahr., the external temperature is only about 60° on an average; the difference of extension which is thus occasioned producing the cracks referred to. He dwells upon the use of iron hooping, and remarks that its object and result are not, strictly speaking, the prevention of extension, but rather the attaining in the outer brick-work of a uniform distribution of the tension and the prevention of its concentration at certain points." ('Builder,' March 17, 1883, p. 362.)

gauge being kept by angle iron ties, grooves being cut in the bank to receive them. On one very hot day about 2 P.M., as Mr. Mansergh was riding down the line, he was very much surprised to find in two places the rails 'up in the air.'" "The first rise was 2 feet 9 inches above the bank in the centre, and 8 metals were off the ground; the second rise was 2 feet 3 inches, and 6 lengths were off the ground." The lengths of these "anticlinals" corresponded respectively to 192 feet and 144 feet.

Mr. Mansergh adds:—"I presume that this bit of road had been riveted up early some unusually cold morning, and was therefore abnormally short. When the heat expanded the metal, the angle ties were held fast in the hard baked grooves, and the rails had no alternative but to set their backs up as we have seen them. They gradually settled down into their places as the evening came on." A lateral movement was also observed. "I had frequently noticed, when riding on the engine in the early morning, a clear space of ½ inch to ¾ inch between the outside rail of a curve and the fine sand ballast packed against its side, caused no doubt by the road having worked over laterally so as to lengthen itself during the heat of the day, and come back again at night."

Mr. B. Baker, C.E., in a paper on the Forth Bridge (British Association Report, 1882) gives several very instructive examples of the effects of expansion and contraction in engineering structures. He states that on a hot sunny day the "Britannia Tube was found to warp 3 inches laterally and 2½ inches vertically where free to move." "Stone buildings and arches are no exception to the rule; indeed the author, from instances that have come under his own knowledge, is satisfied that the stresses due to changes of temperature are often relatively far more severe in stone than in iron arches." "In the Southwark Bridge grooves had to be cut in the masonry to admit of the free expansion of the cast-iron spandrils, which had been fractured in several instances, though the arch was only 240 feet span and the spandrils were not continuous across the piers." In the case of a gasworks roof, "which had fallen down like a pack of cards, he had traced the cause of the accident unmistakably to the expansion of the iron slate-battens, which were exposed to exceptionally high temperature at times." Mr. Baker considers that 12° corresponds to a ton per square inch stress. (Pp. 429–30.)

But not alone in large structures is it necessary to guard against expansion and contraction. In laying small sheets of lead or zinc the metal must be left free to move, or it will quickly rupture by changes of temperature. Hence in all good roof-work, if of lead or zinc, soldered joints are rigidly excluded. Notwithstanding all these precautions, one has only to examine an old lead roof to find it covered with ridges and puckers. These ridges arise from the accumulated small superficial expansions which imperceptibly affect the lead, as Mr. Mansergh's rails were affected; but the low tensile strength and ductility of the metal will not allow it to regain its form by contraction. The anticlinal ridges, instead of being the result of one heating, as is the case of the railway metals, are the accumulated effects of many hundreds of such movements.

It is, however, in vessels lined with lead that the most perfect example of this class of distortion occurs, for the lead in such cases has very little play. Who has not noticed the ridges on an old bath lined with lead?

A most interesting illustration of the accumulated results of small movements taking place from day to day in materials of a ductile nature, subjected to frequent changes of temperature, is the bottom of a butler's pantry sink, of which I give an Ink-photo, Plate VI. p. 28. The alternate expansions and contractions in this case have been due to the ordinary alternations of hot and cold water to which such vessels are subject, continued over a period of nine years. The ridge appears to have worked out from under the two taps as a centre, and the resultant crescentic fold is as perfect as any anticlinal in nature.

But such movements as these are not confined to metals, Mr. C. M. Burns, as quoted by Dr. Alexis A. Julien, in a paper "On the Decay of Building Stones of New York city,"* describing a slab of white marble-veneering 2 inches thick, on the face of St. Mark's, Venice, situated "on the south side of the northernmost of the five portals just behind the columns, and about 5 feet from the pavement." Dr. Julien says:—"The slab is 11 feet and 2 inches long and 1 foot and 6 inches wide; it is hung to the backing by copper hooks driven into the brickwork, but the lower part, for a distance of 5 feet and 7 inches, bulges out 2¾ inches from the backing." In the words of Mr. Burns:—"The exposure is directly westward, and I found that it became decidedly warm in the afternoon sun, while the backing would be likely to keep its temperature lower. Though the outer surface is somewhat weatherworn, I could not find the slightest tendency to fracture in any part"†. The behaviour of this stone is precisely, but in lower degree, the same as that of a sheet of lead under the conditions described.

My attention has lately been called to the buckling of plates on the sides of a series of girder-bridges. Some of these have domed up from ⅝ to ¾ inch in plates 1 foot 8 inches wide. The effect is quite striking, and I am satisfied it is mainly the result of changes of temperature, as in every case it is the south side exposed to the midday sun which is most affected.

It would be easy to enumerate further examples of the effects of alternations of temperature, of a similar nature; but sufficient have been given to enable any one to follow my reasoning, and the application of the facts detailed.

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* Proc. New York Academy of Sciences, 1883.

† 'The American Architectural and Building News,' 1882, p. 118.

CHAPTER IV.

MECHANICAL EFFECTS OF EXPANSION BY HEAT AS DETERMINED BY EXPERIMENT ON VARIOUS MATERIALS.

LINEAR EXPANSION.

Behaviour of Metals.

IN order to ascertain more exactly the way in which the changes of form assumed by various materials when subjected to varying temperatures are brought about, I made the following experiments :—

A strip of lead 1½ inch wide, weighing 12 lb. to the superficial foot, was fastened down to a deal board at points 4 feet 6 inches apart. The flame of a blowpipe was then brought to play upon it, and moved rapidly along the strip; the lead quickly began to bow upwards until the highest part was 1½ inch above the board.

This was the extreme height to which I was able to raise it by one heating. On leaving it to cool it fell to ¼ inch above the board, and after 24 hours' rest it settled down to a little over $\frac{3}{16}$ of an inch. (Plate I. p. 19.)

It is evident from this result that the lead, though free to contract, does not regain its original form, and exemplifies in a more intense and perceptible way the cause of the ridging-up of sheets of roofing and other lead already described. Further experiments by re-heating were made.

SUPERFICIAL EXPANSION, OR THE EXPANSION OF SHEETS OR SURFACES.

My object in these experiments was to discover in what way differential expansion would show its accumulated results on sheets of lead of different forms and thicknesses. Also to attempt to find out what conditions determined the yielding at the parts where the metal buckled or ridged up as the case might be.

Experiment No. 1.—The first sheet I experimented upon was a piece of old sheet lead originally about 6 lb. to the foot that had been used in forming a down-spout.

I flattened it out, which produced lines of weakness in the old creases. It measured 1 foot 6 inches by 6 inches. I nailed it down by the edges to a deal board, and played the flame of a blowpipe over it. The lead rose in a longitudinal ridge traversing the centre of the plate, with transverse ridges or spurs branching from it. I pressed down the lead to the board between the protuberant parts, and heated and reheated it. The ridges became more and more developed until they assumed the appearance given in the illustration (Plate III.). The greatest elevation of the ridge was ¼ inch. At one part the metal was by accident partially melted, forming an elliptical depression. The experiment lasted over three evenings.

Experiment No. 2.—The next experiment was made with a circular disk of 7 lb. lead, nailed by the edge to a deal board (Plate II. fig. 4). It measured 3¾ inches in diameter between the fastenings.

After repeated heatings and coolings it rose in a domical form ⅛ inch above the normal plane. On taking it off the board the concave side showed a repetition of the exterior form, as if it had been chased out.

Experiment No. 3.—I next nailed a sheet of 7 lb. lead to a deal board. It measured 1 foot 7 inches by 8½ inches between the fastenings.

Plate I

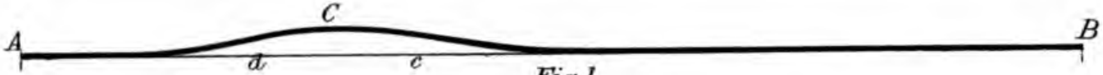


Fig 1.

Fig 2.

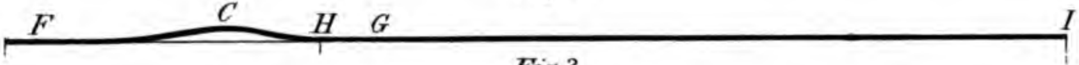


Fig 3

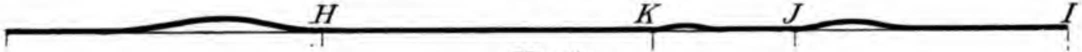
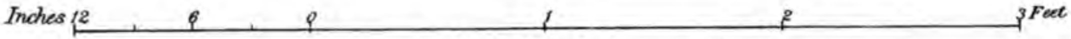


Fig 4.



Scale to Figs 1-4.

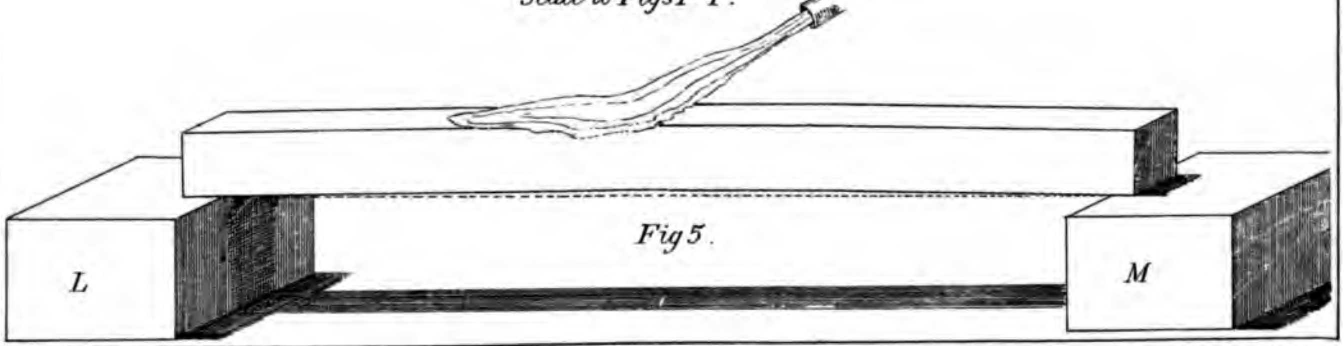


Fig 5.

MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

Sprague & C° Photo-litho London

PLATE I.

Experiments in Linear Expansion.

Fig. 1. Side view of strip of lead 1½ inch wide, weighing 12 lb. to the superficial foot, screwed down to a deal board at A and B. It was laid flat on the board, as shown by the line *d e*. After one heating with the blowpipe, an anticlinal arch rose at C. The strip measured 4 feet 6 inches from A to B, and rose 1½ inch at C.

Fig. 2. The same strip, after being allowed to cool. It took a permanent set at C of a little over 3/16 of an inch.

Fig. 3. The same strip. It was re-heated with the blowpipe, when the anticlinal, C, rose 1 inch. It was then pressed down at F and G and re-heated. Afterwards it was nailed to the board at H and again heated. The anticlinal rose ¾ inch, and cooled to a permanent form ⅝ inch high at C.

Fig. 4. The same strip. The lead was now in a state of tension between H and I. On heating, it was some time before it began to show any signs of movement. When it began to rise it went up rapidly to an anticlinal ⅞ inch high. I then pressed it down as before, and nailed it at J. Permanent anticlinal, ⅜ inch high. I now heated the metal from H to J, and nailed it down at K. An anticlinal rose ¼ inch high, and took a permanent form at ⅛ inch. (See p. 17.)

Effects of Differential Expansion on Stone.

Fig. 5. Bar of Caen stone, measuring 14·448 inches at 60° Fahr.: scantling 1¾ inch × 1 inch. It rested at each end flatways on a brick, L and M. On the flame of a blowpipe being passed over the top surface it arched up 1/16 inch, as shown. It measured 14·464 inches after it had cooled a little. (See experiment No. 3, p. 24.)

On the flame of a blowpipe being brought to play upon it as before, it arched up in a more regular way than in the first experiment, and after repeated operations it settled into three protuberances, having an irregular linear arrangement. The lead in this example was not pressed down at all, but allowed free play to assume whatever form it liked. I then cut star-like gashes into one of the protuberances, about half through the lead, with the effect after re-heating of ridging up this part at an angle. The experiment was made in 1882. I have kept the lead on the board in my bedroom window ever since, exposed to the ordinary variations of temperature. The ridges are higher in summer and lower in winter, but have become permanently further raised about $\frac{1}{10}$ of an inch. As the wood itself is subject to expansion from moisture and shrinkage from drying, it is impossible for me to say how much is due to the movement of the wood, and how much to the varying expansion of the lead. The modelling of the surface is varied and very instructive. (Plate IV. p. 28.)

Experiment No. 4.—The next experiment was of a similar nature, with a sheet of 4 lb. lead, 1 foot 5½ inches by 9½ inches between the fastenings. A couple of ridges were developed, one traversing the entire length of the plate, the other forking out from the centre.

After producing these irregularities with the blowpipe, I placed the plate and its wooden bed in the oven, leaving it there for several days together, then placing it in my library, repeating the process pretty often, but at irregular intervals. The effect of the heating and cooling was to develop the ridges much more strongly, so that now they measure in the highest part half an inch above the surface of the plate at its edges. The definiteness of form of the ridges has increased, and the sides have become steeper since the plate has been removed from the last heating in the oven. (Plate V. p. 28.)

Experiment No. 5.—After these experiments with sheets of lead it occurred to me to try zinc. For this purpose a sheet of that metal 15 inches by 12 inches, No. 16 gauge, was riveted to a plate of malleable iron of the same size and $\frac{1}{8}$ inch thick. It is evident that the zinc could only be affected by the differential expansion of the two metals.

The coefficients of expansion, according to the tables compiled by Kinnear Clark, are $\frac{1}{61,200}$ for zinc and $\frac{1}{147,420}$* for forged iron. After one heating in the oven from 62° F. to 180° F. the zinc had very perceptibly buckled, and had forced the iron plate, to which it was riveted, into a concave shape at the bottom. I now repeatedly heated the combined plates in the oven, but never to over 200° F., generally to much less. The zinc is now extremely convex, of a pretty regular curvature, rising about half an inch above the true plane.

If the plate had been larger there is little doubt that the zinc would have arranged itself in folds and creases instead of rising in a domed form.

Deductions from the preceding Experiments.

These experiments show that when a sheet of metal is heated, but secured from lateral enlargement, its behaviour is regulated by the thickness and ductility of the metal. If sufficiently thick or rigid to support itself in the domed form, it assumes and retains that shape. If, on the other hand, it is too weak to support itself as a dome, the superfluous horizontal extension in all directions, by expansion, causes the plate to adapt itself to the new conditions by ridging-up. The form and direction of these ridgings can be to a large extent governed by the manner in which the heat is applied. If a regular heat is applied affecting the plate equally in all its parts, the ridgings will be governed by the accidental lines of weakness that may exist in the plate. If, on the other hand, the heat is locally applied as by a blowpipe, the metal bosses up where the flame is played upon it. In this way the form of the protuberances can be to a large extent moulded at will. No doubt changes take place in the thickness of the plate at various points, but I have been unable to measure them.

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* 'Manual of Rules, Tables, and Data for Mechanical Engineers,' p. 336.

EFFECTS ON VARIOUS STONES OF DIFFERENTIAL EXPANSION.

The experiments already detailed being made with thin sheets of metal having a high conductivity, the temperature on the opposite sides of the plate would not differ sufficiently to affect the result. I now conducted a series of experiments with rocks of various descriptions, in which, through the thickness, the less conductivity of the stone, and the way the heat was applied, the differential expansion had marked effects, which I proceed to describe.

Experiment No. 1 (see Plate II. fig. 1).—A bar of fine hard light brown sandstone, square-dressed to a smooth surface, measuring between two fixed points 7·346 inches long at 61° F., and roughly speaking $1\frac{3}{4}$ inch by 1 inch scantling, was placed with its ends resting flatways on two supports. The flame of the blowpipe was brought to bear upon the upper surface until it expanded to 7·385 inches. The stone was hot enough to melt solder but not lead—perhaps 500° F. on the top surface. As the blowpipe played upon the stone it became, in places immediately under the flame, momentarily heated on the surface to a bright red heat, and the sharp edges were burnt off; the stone became when cool of a darker brown, but apparently was not otherwise altered by heat. The stone arched upwards against gravity in a most remarkable manner to the extent of $\frac{1}{32}$ of an inch. A second heating brought it up to not less than $\frac{1}{16}$ inch, at which it took a permanent set.

The measurements were taken in this and other cases with a pair of steel callipers which measure very accurately to $\frac{1}{1000}$ of an inch. Care was of course taken to avoid as much

Plate II

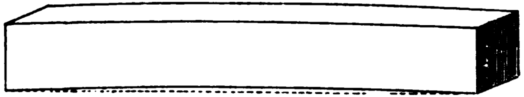


Fig I.

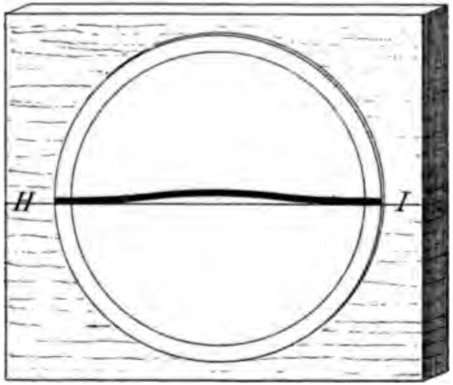


Fig 4

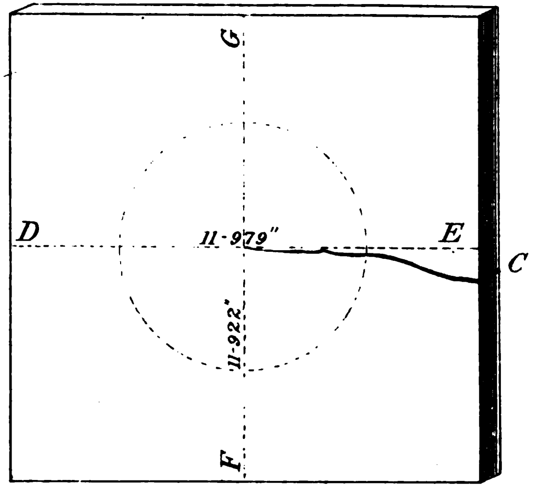


Fig 3.

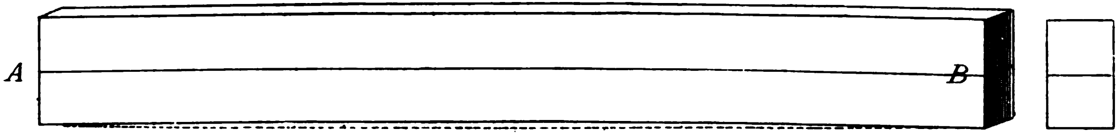


Fig 2.

MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

Sprague & Co Photo-litho London

PLATE II.

Effects on Stone of Differential Expansion.

Fig. 1. Bar of fine hard light brown sandstone 7·346 inches long; scantling 1¾ × 1 inch. It was supported like fig. 5, Plate II., and heated on the top surface with a blowpipe. It arched up as shown with the first heating $\frac{1}{32}$ of an inch, and at the second over $\frac{1}{16}$. (See experiment No. 1, p. 22.)

Fig. 2. Bar of Sicilian white marble, measuring 14·465 inches at 65° F.; scantling 1¾ × 1 inch. This was placed on edge on supports as before. A line was drawn on the side at A B. On heating with a blowpipe it arched up not less than $\frac{1}{16}$ of an inch. It took a slightly arched form permanently, and also suffered torsion. (See experiment No. 7, p. 24.)

Fig. 3. Slab of Sicilian marble, 11·922 × 11·979 inches, and ¾ inch thick. This was placed upon two bars of slate. It was heated with a blowpipe on the upper surface. The flame was rather small, and was kept mostly near the centre within the circle of dotted lines, but was also moved about. The slab became very slightly convex. Eventually it cracked at one side at C as shown, opening out at the edge about $\frac{1}{32}$ inch; the crack now extends to the centre. As the slab cooled the crack closed up. The crack was the result of the circumferential and radial expansion of the centre part of the slab, within the dotted lines, and shows that a considerable bursting strain was developed. The total amount of expansion from D to E was 0·013 inch, and from F to G 0·015 inch. It permanently expanded 0·005 inch each way.

The crack at C opened with the re-heating of the centre of the slab, and closed with the cooling; uncoiling, as it were, like a spiral spring.

A similar slab of fine sandstone, supported in a similar way and heated on the underside with a gas-stove, became slightly concave on the upper surface, but did not rupture. The heat was more evenly distributed than in the previous example, though less at the edges than the middle. It expanded 0·013 inch and 0·014 inch respectively across the centre. The temperature at the top was sufficient to melt fusible metal. (See experiments No. 11 and 12, p. 26.)

Fig. 4. Circular sheet of 7 lb. lead nailed to a board at the edges. After repeated heatings and coolings the lead rose in the dome-like form shown in section H I, drawn across the centre of the disk. (See experiment No. 2, p. 18.)

as possible the heat affecting the callipers. Any error this way would of course make the apparent expansion of the stone less than the actual.

After the second heating it measured 7·396 inches, and became permanently lengthened to 7·366 inches or 0·020 inch.

Experiment No. 2.—A similar experiment was made with a piece of sandstone $6\frac{1}{2} \times 1\frac{3}{4} \times 1$ inch, which also arched upwards and took a permanent set. No accurate measurement was made in this case.

Experiment No. 3 (Plate I. fig. 5).—This was made with a piece of Caen stone (Oolite). The scantling of the bar was the same as No. 1, the length at 60° F. 14·448 inches. It expanded under the blowpipe to 14·464, measured after it had cooled a little. After cooling to normal temperature it measured 14·450. The heat of the surface was probably about 300° F.

This bar also rose in an arch about $\frac{1}{16}$ inch. It remained hog-backed for a considerable time, and even now, a year afterwards, it is appreciably though much less arched. It measures now 14·446 inches, but whether it has permanently shrunk, or only worn at the points of measurement, I cannot tell.

Experiment No. 4.—This was made with a bar of St. Helens sandstone (a fine micaceous quality much used for hearthstones) measuring 14·424 inches. It took a minute but perceptible "hog's-back," and when cooled measured the same as before heating.

Experiment No. 5.—A bar of Hare-Hill sandstone, measuring 14·455 inches, scantling same as before, was heated the same as No. 4, with precisely similar results.

Experiment No. 6.—A similar bar of Irish black marble, 10·764 inches long, after being heated with a blowpipe *permanently* extended to 10·768 inches.

Experiment No. 7.—A bar of Sicilian white marble 14·465 inches long at 65° F., $1\frac{3}{4} \times 1$ inch, was placed on edge supported at each end on a brick. This was heated with a blowpipe, but did not at any point under the flame become red-hot. It arched up or "hog-backed" at least $\frac{1}{16}$ of an inch. A line had been drawn along the centre of the side, and this line, on looking along it, showed the arching very plainly. It measured along this centre line while hot 14·491 inches, so that it had expanded 0·026 inch. On cooling down to 65° it measured 14·476, showing an extension for the time of 0·011 inch, and it remained permanently arched.

Seven days afterwards it measured 14·475 inches. (Plate II. fig. 2.)

It now, after the lapse of nearly fourteen months, measures 14·474 inches, that is to say, it remains expanded 0·009 inch. The arching of the stone is still quite perceptible on looking along the centre line. It also has a slight twist, as may be seen on applying the bar to a plane surface. This is doubtless due to the flame of the blowpipe playing partly on one side as well as the top. The twist, or "skew wift," is common to all the stones that have been permanently distended. There is no perceptible alteration in the structure of the stone.

Experiment No. 8.—This was with a bar of fine-grained Burnley sandstone, placed on edge in a similar manner to No. 7. On heating to redness in the centre it arched considerably, but in a broken-backed sort of way, through the heat being mainly confined to the centre. At 65° it measured along the centre line 14·453 inches; when heated it lengthened to 14·479 inches or 0·026 inch. On cooling to 65° it measured 14·456 inches, a difference of only 0·003 inch from its original length. It now, after a lapse of nearly fourteen months, measures 14·456, showing that the lengthening, though small in amount, is permanent. It does not retain as much curvature as No. 7, but the arching, as well as a slight twist, is very perceptible on applying it to a true plane surface.

The whole of these bars were, before being experimented upon, rubbed to true surfaces.

Experiment No. 9.—This was with a bar of fine-grained grey sandstone. It was placed upon supports at each end, as in the other instances, but on the flat, and was heated to redness in the centre, but only superficially, as in all the other experiments. At 60° it measured on a centre line on the side 14·443 inches. In this case, the centre line being on the side and the stone on the flat, the measurement when heated was taken across the back of the arch; it was 14·483 = to an expansion of 0·040 inch. In no case was the measurement taken while red-hot; indeed, on withdrawing the flame of the blowpipe the redness ceased almost instantly. It cooled down to 14·450 = to a lengthening of 0·007. The bar was very decidedly arched when hot. After two days the lengthening was reduced to 0·006. It now measures 14·448 inches at 60°, or remains permanently lengthened 0·005 inch.

It remains arched more than No. 8, and it is also twisted.

Experiment No. 10.—This was with the same bar of Irish black marble as described in No. 6. On heating, but not to red heat, it expanded to 10·800 inches, its length before the first heating having been 10·764 = total expansion 0·036. When cooled to normal it measured 10·778 inches = permanent lengthening of 0·014, of which 0·004 was due to previous heating. It broke immediately after measuring, so that there may have been a minute rupture affecting the length. It arched up only slightly.

Experiment No. 11.—A slab of Sicilian marble 11·922 inches by 11·979 inches and ¾ inch thick was supported on slate bars, and heated on the top surface with a blowpipe; it became slightly convex, and eventually ruptured at C, Plate II. fig. 3. The fracture closed up on cooling, and opened again on re-heating.

Experiment No. 12.—A slab of fine-grained sandstone, the same size and thickness as the preceding, was heated on the underside by a gas stove. It became slightly concave on the upper surface, but did not rupture. The details of these two last experiments are given in the description of Plate II.

What the Experiments show.

These experiments conclusively prove that rock is not the immobile material we are apt to think it. A further set of experiments was made, which will be detailed hereafter, to determine, as nearly as I could, the coefficients of expansion for each kind of rock. Indeed such determinations preceded in many cases the experiments just described, the same bars having been previously used for that purpose. It was impossible, in the foregoing experiments, to do more than guess at the temperature the stone had been raised to, and what it was when measured. In fact each bar was both intentionally, and from the nature of the application of the heat, of different temperatures at different parts.

If we take the average temperature of the bar in Experiment No. 1 at 500° Fahr. when measured, it expanded $\frac{1}{83,128}$ of its own length for every degree. This is higher than the coefficient of any of the sandstones as given in the table further on, and determined between differences of temperature never reaching more than 160° Fahr.

Not only did the differential heat between the upper and lower sides of the bar—the amount of such difference of temperature being impossible for me to determine—prove sufficient in all cases to very decidedly arch the bar up against its own gravity, but in many cases it gave the stone a decided set or distortion, part of which was retained after the lapse of fourteen months, although its lying in the drawer must have tended to straighten the stone. The bars experimented upon were all reduced to a plane surface on the four sides, so that if placed on another plane surface, like the marble slab of a chimney-piece, the two surfaces would coincide.

Such a test now shows that after the lapse of fourteen months they are all more or less permanently distorted, having suffered torsion as well as bending. It will also be observed that only one stone recurred to its original length, while another (Caen stone) apparently shrank, but of this I cannot feel quite sure, as the surface of the stone may have worn away with frequent measuring, the stone having been experimented upon pretty often.

The Sicilian white marble not only retained the set, being arched up the deep way of the bar, but became permanently lengthened 0·009 inch, or $\frac{1}{1607}$ of its original length.

PLATES III., IV., V., & VI.

Effects of Superficial Expansion on Sheets of Lead.

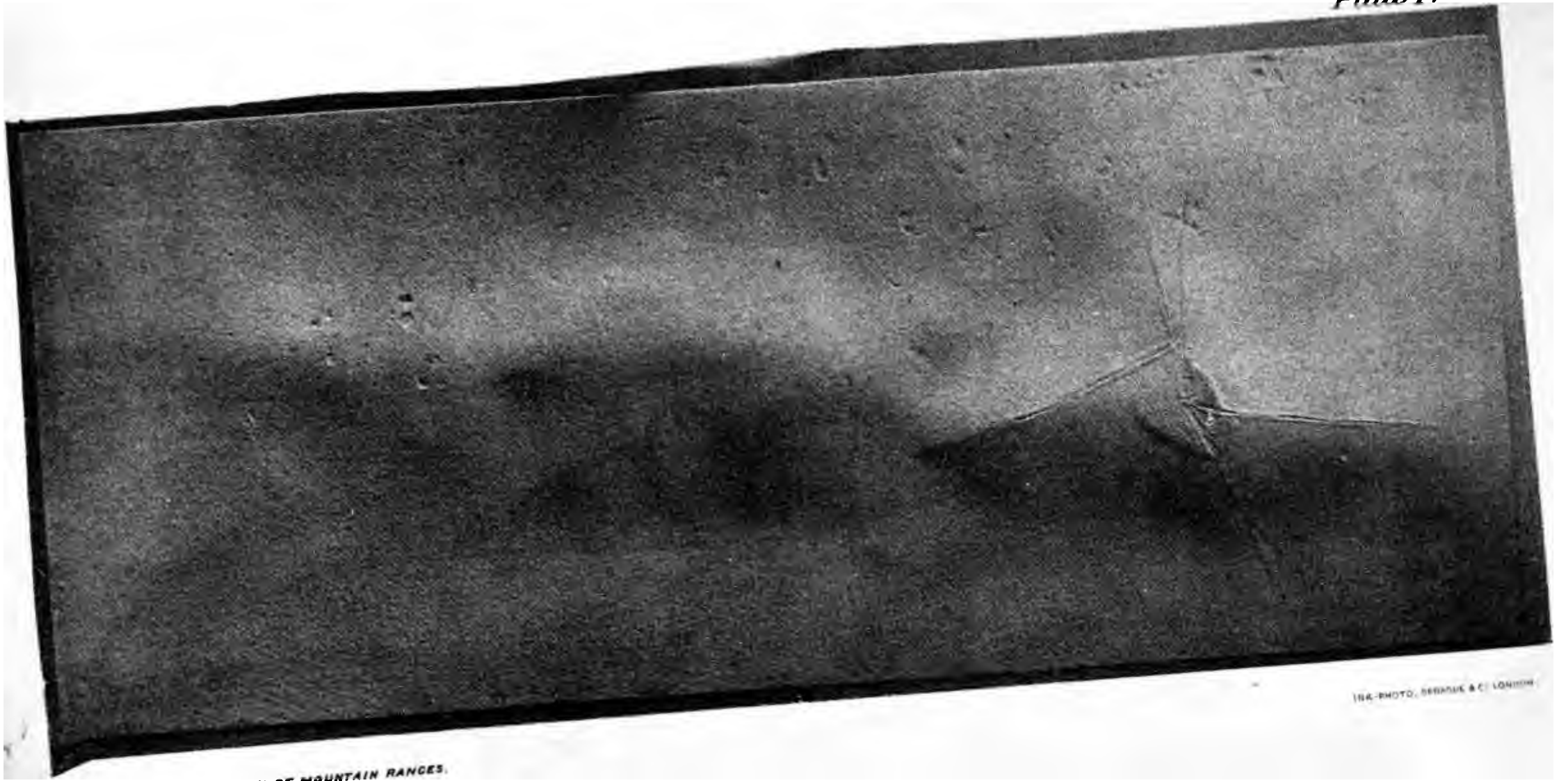
Three of these Plates (III., IV., & V.) are Ink-photos from plaster casts of the sheets of lead experimented upon, as described in pp. 18 and 20, Experiments Nos. 1, 3, and 4.—Plate VI. is an Ink-photo from a cast of a butler's pantry sink, described in p. 15. The lead in this case was very strong, I should think about 10 lb. to the superficial foot.

Plate III

MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

INK-PHOTO. SPRAGUE & Cº LONDON

Plate IV



INK-PHOTO. SPRAGUE & C° LONDON.

MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

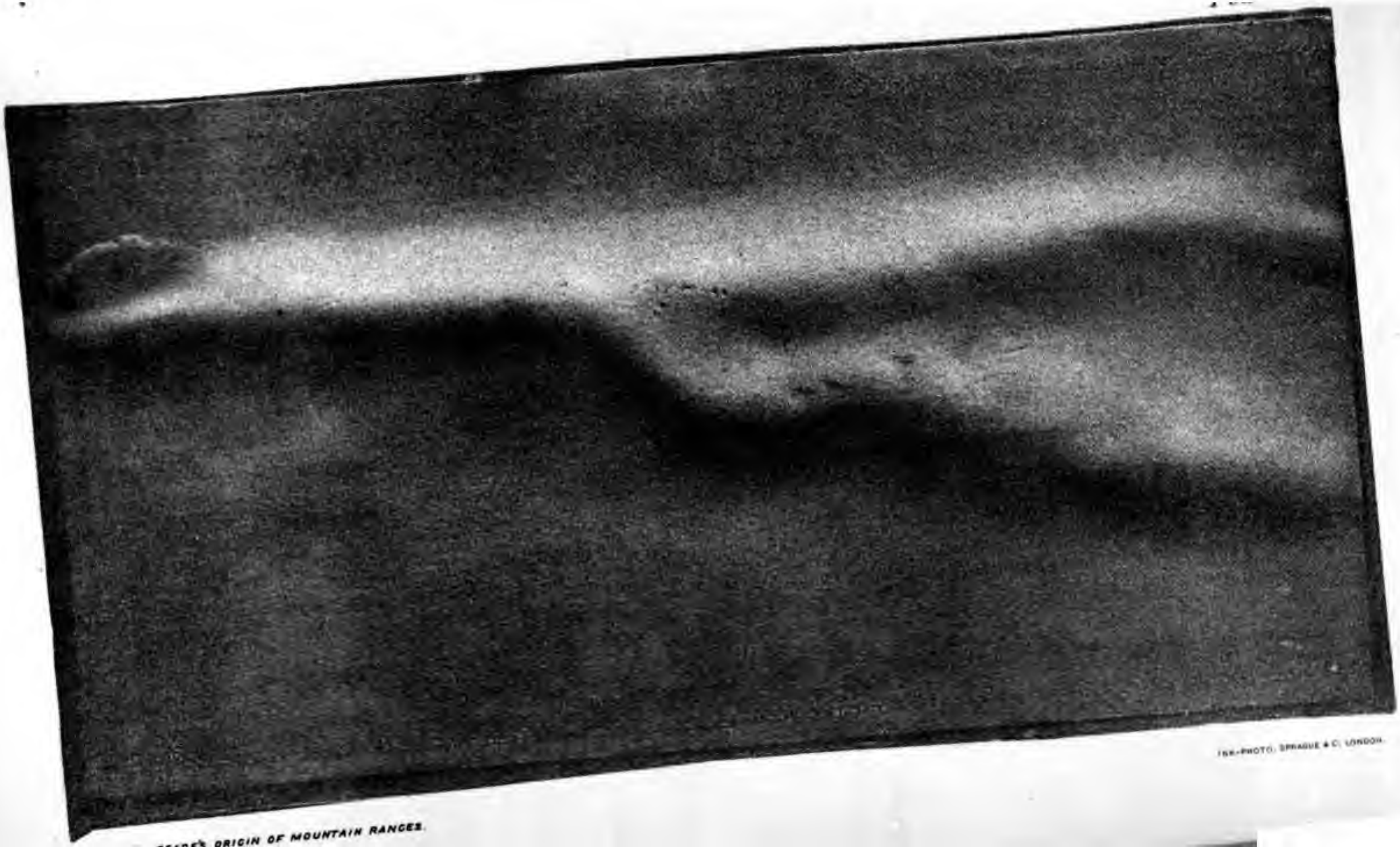
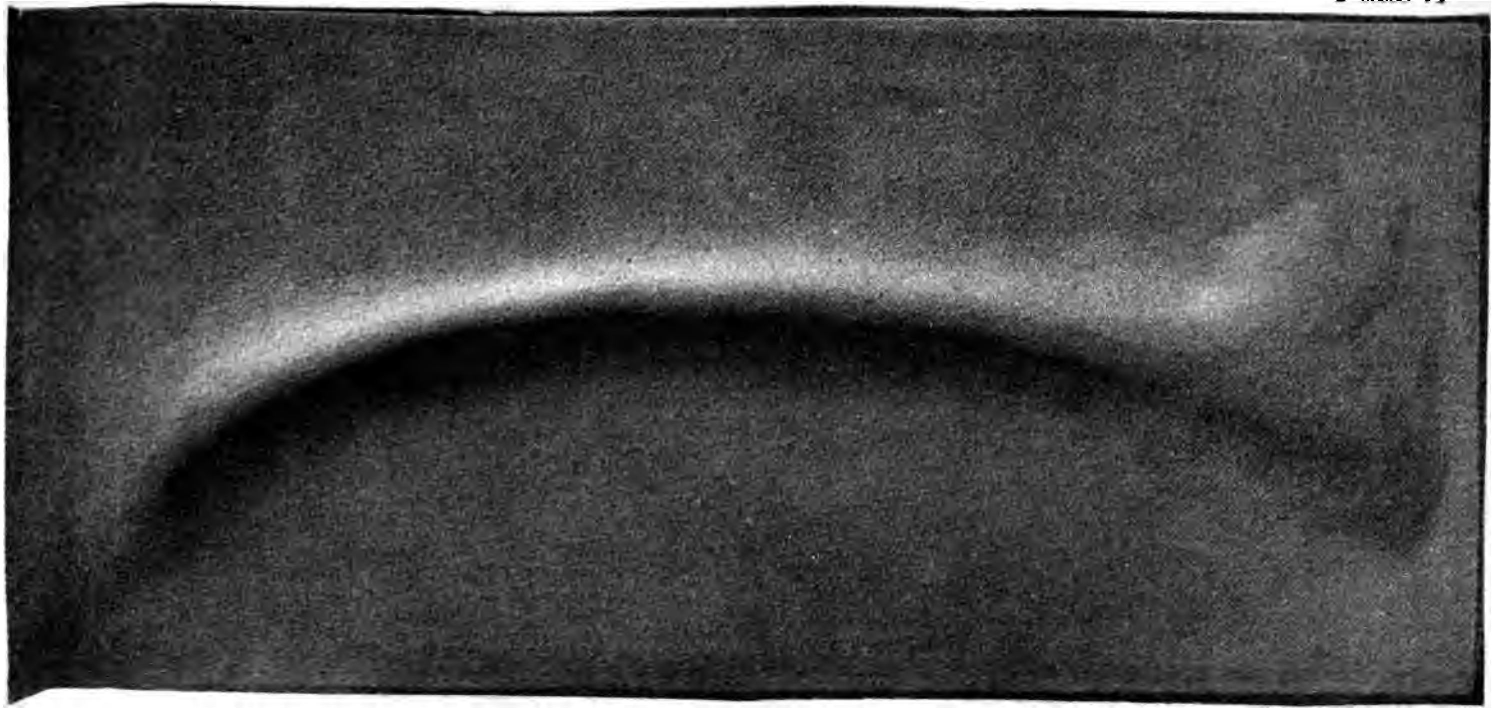


Plate VI



MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

INK-PHOTO SPRAGUE & Cº LONDON

CHAPTER V.

GEOLOGICAL PHENOMENA ASSOCIATED WITH MOUNTAIN-RANGES.

Leaving for the present a further consideration of the application of the facts brought out by the foregoing experiments, let us take a view of some of the geological phenomena we find in connection with great mountain-chains.

General Considerations.

It has been a subject of remark and wonder to more than one eminent geologist, that all the greatest mountain-ranges are, geologically speaking, so comparatively modern. The Himalayas, the Andes, the Alps, and the mountains of the Caucasus have been, to the larger extent, upheaved in Tertiary times*.

That these great ranges constitute the highest land on the Earth's surface, is satisfactorily explained by the fact that they have not been exposed for so great a length of time, as the earlier mountains, to destructive denudation, which acts at an accelerated rate in the higher regions of the atmosphere. This truth was particularly forced upon my attention in working out the figures for my Presidential Address to the Liverpool Geological Society in 1876, "On Geological Time;" by which it came out that the older formations in England and Wales, usually composed of more insoluble rocks, through occupying generally the higher grounds and mountain-districts where the rainfall is greatest, yielded in the aggregate as much solids in solution as the more soluble rocks constituting the Thames Basin *.

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* Ramsay: "The Geological History of some of the Mountain Chains and Groups of Europe." Lectures at the Royal School of Mines, 1875; reported in 'Mining Journal,' January 30th, and February 6th and 13th.

But though we can see plainly why the newest mountains are the highest, it is not at all clear why they should be composed of the newest sediments, or rather the newest at the time of their upheaval. Still this great truth remains, that it is impossible to point to a range of mountains which have been built up of old denuded rocks. Old rocks certainly accompany, and form part of all great mountain-ranges; but they are only discoverable through the removal by denudation of the enormous masses of more modern sediment, with which they were originally covered. This is certainly a fact to make us pause and think, and it seems strange that it should have been so often lost sight of in reasoning upon mountain-building. If we could point to *one* example where a mountain-range had been built up solely of old rocks that had long suffered denudation, and remained at the time of upheaval uncovered by newer sediment, the significance of this association of great sedimentary deposits with mountain-building would be considerably weakened.

But no such example can be produced. On the contrary, as the following illustrations will show, not only great mountain-ranges, but lesser chains, and even low anticlinal upheavals, are, so far as we know, invariably associated with new sedimentation.

GREAT BRITAIN.

To begin near home, the mountains of Wales, the north of England, and north of Scotland were upheaved only after strata, estimated at over 8 miles in maximum thickness, were deposited over the area of the British Isles †.

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* Reprinted in 'Chemical Denudation in Relation to Geological Time,' p. 12.

† The Lower Silurian rocks of Britain are estimated by Murchison at 30,000 feet. 'Siluria,' 5th ed. ch. xiv. p. 354.

The old mountain-systems of North Wales, Cumberland, and Westmoreland are entirely carved out of Cambrian and Silurian strata. The range in which the Rhinogs are situated, which rise to a height of 2400 feet above the sea, is carved out of Cambrian strata almost from base to summit.

Enormous masses of Lower and Upper Silurians have been removed by denudation, yet Merionethshire remains mountainous still. Most probably in succeeding periods, rocks of a later age have been deposited over this area, but if so, these newer formations have long ago been swept away by denudation. With the exception of Carboniferous, Permian, Triassic, and Liassic rocks, in contiguous areas, these later rocks have not been preserved. Though these Silurian mountains may have been, to a certain extent, modified and faulted by earth movements since their primary upheaval, they still stand as monuments of the enormous forces developed in the earth's crust, after the Cambrian and Silurian sedimentation had been completed.

It is not only that the Cambro-Silurian sediments were of great thickness, but they were also of vast extent. They extend to, and thin out on, the Scandinavian continent. They are found in the north and west of European Russia, and again along the Oural Mountains, from which Professor Hull infers they underlie the whole of Central Russia, but in very much diminished thickness*. In the North of France the Lower-Silurian rocks attain to great vertical dimensions. In the Department of the Sarthe they are estimated at nearly 20,000 feet. Silurian rocks have been proved to underlie the Cretaceous strata of Northern Belgium, and they are largely developed in Spain †.

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* "On the Geological Age of the North Atlantic," Trans. of the Royal Dublin Society, April 1885, vol. iii. series 2, p. 311.

† See Map, showing "the comparative thickness and depth of deposition of the Cambrian and Lower-Silurian rocks in different areas" by Dr. Hicks. Q. J. G. S. Nov. 1875, p. 558.

The next most important mountain-system in England and Wales is carved out of Carboniferous strata. Portions of the Pennine Chain, forming the watershed between the Irish Sea and the German Ocean, in the north of England, rise to a height of 2500 feet [*]. The Mendip Hills and a large part of South Wales are formed of Carboniferous strata. These beds, as was first shown by Mr. Godwin-Austen, and afterwards proved by various well-borings, are connected by a subterranean ridge of Palæozoic rocks passing under the London Basin and the north of France with the disturbed Coalfields of Belgium [†].

Here, again, the conditions that preceded the upheaval were the deposition of great thicknesses and extended areas of sediment. The Coal-measures, Millstone grit, and Yoredale series in South-east Lancashire are estimated by Prof. Hull at over 12,000 feet. The Mountain Limestone of Derbyshire attains a maximum thickness of 4000 feet, and yet its base is never seen. Prof. A. Geikie says:—"This Pennine region appears to have been the area of maximum depression during the early part of the Carboniferous period in Britain" [‡].

In Ireland the Carboniferous Limestone occupies a large area, and attains a maximum thickness in the west and south-west, where it measures at Limerick, according to Mr. Kinahan, 3600 feet [§].

In Scotland the Carboniferous beds occupy the whole of the country between the Forth and Clyde.

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[*] Phillips's 'Geology of Yorkshire': Part II.—Mountain Limestone District, published in 1836. This is still the best work on the district, and well worth studying in the physical portions.

[†] See section of Coalfields of Somerset and Bristol, Liége, and Westphalia, in Prestwich's 'Chemical and Physical Geology,' p. 260.

[‡] 'Text-book of Geology,' 1st ed. p. 738. For details of distribution, and thickness of Carboniferous rocks, see Woodward's 'Geology of England and Wales.'

[§] 'Manual of the Geology of Ireland,' p. 71.

No doubt the Carboniferous area extended seawards into the Atlantic, but to what distance we have no means of knowing.

In all these examples the sedimentary strata are accompanied by volcanic rocks—sometimes interbedded, in others intruded; but of these more will be said as the subject develops.

I have taken these two illustrations because in Britain they are the most important in their effects, but it can be shown that disturbances of the strata have followed the laying down of formations, here not much developed, but in other places on the globe occupying vast areas, attaining great vertical dimensions, and accompanied by a proportionate development of energy, culminating in the folding, crumpling, condensation, and upheaval of the consolidated sediments.

North America.

Appalachians.

Perhaps the connexion between the extent and thickness of the rocks, and their elevation into mountain-ranges is nowhere more apparent than in the region of the Appalachians, made classic by the labours of H. D. and W. B. Rogers, and since more fully worked out by Prof. Lesley and the officers of the Second Geological Survey of Pennsylvania. In the map prepared by Mr. W. J. McGee, "showing the present state of knowledge (1884), relating to the areal distribution of geologic groups," the main outlines of the Carboniferous system in the United States are given. It occupies east of the Rocky Mountains about 400,000 square miles, principally in the valleys of the Mississippi and its tributaries. The map, of course, takes no notice of Carboniferous rocks underlying rocks of a later date, nor of those areas that have been since denuded of Carboniferous deposits. Judging from what we know of the enormous denudations that have taken place even in Tertiary upheavals, we can form a rude conception of the enormous reduction of area and thickness which has taken place in the Carboniferous system of the Appalachians during the vastly greater time it has been exposed to atmospheric and other vicissitudes. To form an idea of the importance of the enormous amount of sediments in connexion with the upheaval of the Appalachian chain, it is necessary in imagination to replace them. It seems to me extremely probable that the whole of the highly folded Archæan rocks to the south-eastwards were once covered with an extension of the same Carboniferous sediments. If we pass from the United States to Canada, we find a fragment of the North-American Carboniferous system still existing, where, on the shores of the Bay of Fundy, at the well-known South Joggins section, it is calculated to reach the thickness of 14,570 feet *. From what we know of the geological behaviour of the rock-systems, we may infer with certainty that this enormous thickness of now isolated beds is part only of a much more extended area of the same nature, if not of the same thickness, preserved from denudation by being situated in a synclinal fold, or by faulting, or by both combined. If we produce the axis of the Appalachian range, we shall find that it actually strikes across this area of Canadian Carboniferous.

The eastern side of the Appalachians, being exposed to the rigours of the Atlantic, would, through the greater rainfall on the coast, suffer more rapid denudation †. And this exposure to the rains of the Atlantic is not a mere modern phenomenon, for the Tertiary and Cretaceous rocks of the coast,

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* 'Acadian Geology:' Dawson, 3rd edit. p. 151.

† The rainfall is given by H. D. Rogers as follows:—Philadelphia, 35 to 55 inches; Pittsburg, 25 to 47 inches; Gettysburg, 30 to 52 inches; New York, 30 to 65 inches—all of which are high; but the number of rainy days is much less than in Great Britain. 'Geology of Pennsylvania,' First Survey, vol. i. p. 57.

from New Jersey to Georgia, show that the waters of the Atlantic have actually laved the sides of the Archæan rocks now forming the eastern flanks of the Appalachians. That there is nothing exceptional in this subaerial wearing away of the seaward slope of the land areas, we may satisfy ourselves in Britain and Ireland. Here the prevalent winds and rains are from the south-west and north-west, and we find in these atmospherically affected areas that the oldest rocks occur at the surface, having been uncovered by denudation. In the Outer Hebrides, little but the oldest gneissic rocks are met with. On the mainland of Scotland, from the Mull of Galloway to Cape Wrath—with the exception of the Carboniferous rocks of the Clyde Valley, preserved by being let down in an immense trough fault, and the Tertiary rocks of Mull and Skye, so admirably unravelled by Prof. Judd—there is little to be found but Silurians and Cambrians.

In the north, from Skye to Cape Wrath, the still older Archæans come to the surface.

In Ireland, the oldest rocks are found on the west coast in Donegal, exposed to similar atmospheric conditions. The same is true of the coast from Galway Bay to Broadhaven. The same generalization holds true even of the west coast of England and Wales. Fortunately it is not open for any one to say in the case of Scotland, "These old rocks appear at the surface because newer ones have never been laid down upon them;" for, leaving out of account the fact that the very constitution of these old rocks shows they have been buried under enormous masses of their own age since removed, Secondary rocks have been discovered associated with them. A small patch of Carboniferous in the wild ravine of the Innimore of Ardtornish was brought to light by the labours of Prof. Judd*. As he has so lucidly and conclusively shown, the unexpected fragment has been preserved through being let down 2000 feet by faulting, and so inserted in the rocky framework of the land like a piece of mosaic. These geological fragments are as certain evidence of the former extension of Secondary rocks over a large part of Scotland as is the mosaic pavement of Uriconium of the former presence of the Romans in Britain. (See Plate VII. and description, p. 37.) But it will take too much space here to develop the subject fully. If I have brought sufficient facts forward to show that there must formerly have existed to the eastwards of the Appalachians, and probably under what is now the Atlantic, extensive Carboniferous beds, my present purpose is achieved.

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* "Secondary Rocks of Scotland," 3rd paper, August 1878, p. 684.

According to Dana, who divides these deposits into Subcarboniferous and Carboniferous, the former attained a maximum development of from 4000 to 5000 feet *. These are, however, but representatives of one of the several systems out of which the Appalachians were built, as over a large area they rest upon Devonian, Silurian, and Cambrian strata.

Prof. Lesley says that on the Susquehanna river above Harrisburg, the eleven Palæozoic formations from the top of the Pottsville conglomerate measure at least 26,000 feet; the same formations measure along the Ohio river above Cincinnati less than 3500 feet; and he estimated that at Pittsburg, midway between the eastern and western outcrops, the Potsdam sandstone lies at a depth of 15,000 feet †.

The Pittsburg coal-bed occupies in Pennsylvania an area of 2500 square miles of an estimated average thickness of 8 feet. Prof. Lesley considers that it and its companions, the upper productive Coal-measures, formerly extended into the State of New York and even Northern Ohio, and that it is not improbable that its original area crossed Lake Erie and Lake Ontario into Canada ‡.

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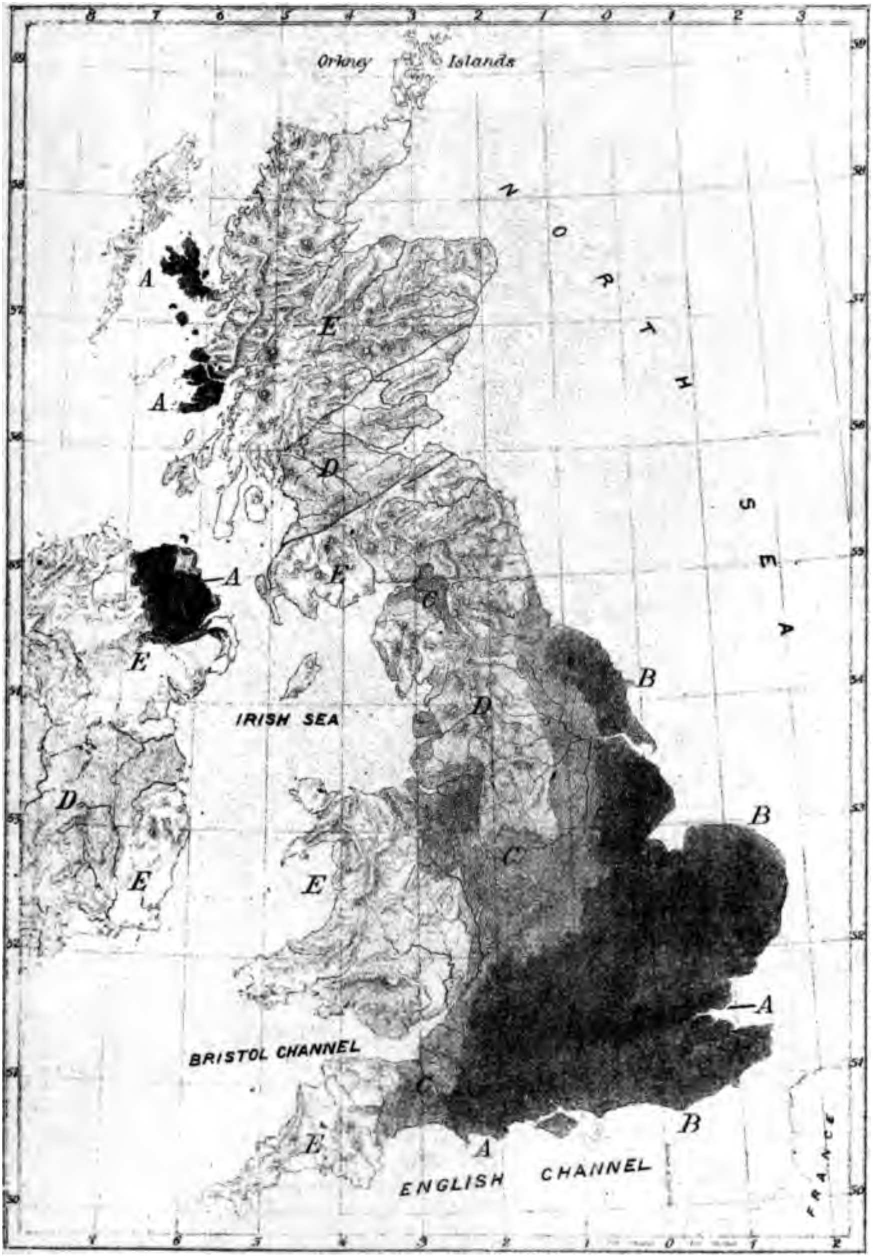
* 'Manual of Geology,' 2nd edit. p. 305.

† "The Geology of the Pittsburg Coal-region," read before the American Institute of Mining Engineers, February 1886, p. 15.

‡ Ibid. p. 8.

Plate VII



MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

INK-PHOTO. SPRAGUE & Cº LONDON.

PLATE VII.

Map of Great Britain and part of Ireland, showing by varying depth of shading the present distribution of some of the Rock-systems; commencing with white for the oldest rocks, and ending with the deepest shade to represent the Tertiaries.

A. Tertiaries.
B. Cretaceous and Oolites.
C. Lias, Trias, and Permian.
D. Carboniferous.
E. Old Red Sandstone, Silurian, Cambrian, and Archæan.

The object of this Map is to represent at once to the eye the relative ages of the different parts of the British Isles. It shows plainly that the oldest strata are in the mountainous districts, and enables us to grasp the high probability of the former extension of the newer strata over most of the mountain areas, from which they have been worn by denudation. Hence it may be called a "Denudation Map."

The highest pile of Coal-measures has been preserved in Greene County, near the State line. The upland summits have an elevation of 2000 feet above the tide, and the bottom of the great conglomerate is 500 feet below tide. But this is not the full thickness, as an unknown quantity has been eroded from the summit.

Prof. Lesley estimates that erosion has taken place to the extent of 25,000 feet in Blair County and at least 30,000 feet at Harrisburg *.

The Coal-measures of the Pittsburg region are about 2000 feet thick, and contain at least fifteen workable beds of coal. "They lie upon each other like the layers of a sea-shell, have a gentle south-western slope of about 2600 feet in 160 miles, and, if planed off to a flat surface, the outcrops at the limits of this area would be as continuous as the lines of wood-layers in a plank planed by a carpenter at a low angle across grain." †

Prof. Dana, who has done much to elucidate the mysteries and systematize the knowledge of mountain-structure, considers that the Palæozoic systems are here conformable, and the total thickness of the whole group is 40,000 feet ‡. H. D. Rogers estimates that, according to careful measurements, their aggregate thickness cannot be less in Pennsylvania than 35,000 feet §. Dr. Sterry Hunt says || the total thickness of the Palæozoic strata along the Appalachian Chain is about 40,000 feet; while the same formation in the Mississippi Valley, including the Carboniferous Limestone which is wanting in the east, have, according to Mr. Hall, a thickness of scarcely 4000 feet. It will be well to

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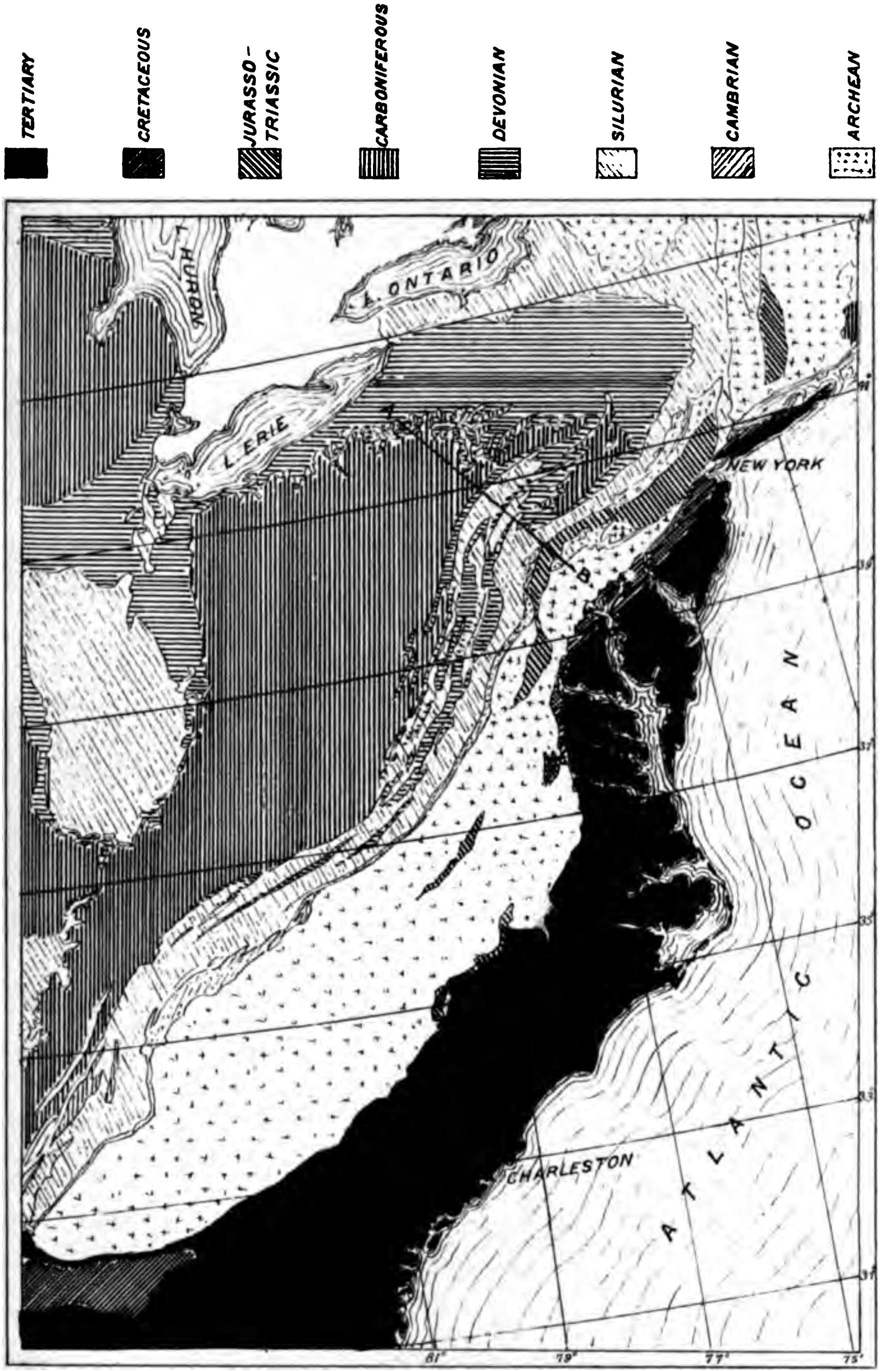
* "The Geology of the Pittsburg Coal-region," read before the American Institute of Mining Engineers, February 1886, p. 12.

† Ibid. pp. 6 & 7.

‡ 'Manual of Geology,' 2nd edit. p. 748.

§ 'Geology of Pennsylvania,' vol. i. p. 60.

|| "American Geology," American Journal of Science, May 1861.



MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

Sprague & Co. Photo-litho London

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Plate VIII.

give, after the preceding description of the geological formations associated with this most interesting mountain-system, a general idea of its leading physical peculiarities.

Physical Aspects.—Dr. Arnold Guyot says * :—"The upheavals of ancient rocks which constitute this well-connected physical structure, for which as a whole it is proper to retain the common name of the Appalachian System, extend in an undulating line thirteen hundred miles in a mean direction of N.E. and S.W. from the promontory of Gaspé upon the Gulf of St. Lawrence to Alabama, where terminal chains sink down and are lost in the recent and almost horizontal strata of the Cretaceous and Tertiary formations which cover the greater portion of the surface of this State. This long elevation is composed of a considerable number of chains sensibly parallel to each other, occupying more particularly the eastern part which faces the ocean, and of an extended plateau which prevails towards the west and north-west, and descends gradually towards the inland valleys of the St. Lawrence, the Lakes Erie and Ontario, and the Ohio river.

"The plain on which this system rests is in New England about 50 miles wide; it disappears near the Hudson, New Jersey, and gradually increases towards the south to over 200 miles. Its elevation above the sea at the foot of the mountains is in New England from 300 to 500 feet.

"From the neighbourhood of the Bay of New York, where it is nearly on a level with the sea, it rises south to over 1000 feet. On the west the tablelands preserve a mass elevation of 1000 feet or more, the river being scooped out to a depth of from 400 to 600 feet, thus reducing the altitude of the Ohio river to one half that of the surrounding lands.

"The system is composed of a series of long folds or chains that run parallel to each other, often with great regularity.

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* "On the Appalachian Mountain-System," American Journal of Science, March 1861.

In the middle region they present the appearance of long and continuous walls, seldom varied by any peaks or crags."

It is further pointed out that the system has no central axis to which the secondary chains are subordinated; in this respect being unlike the Alps and like the Jura. It is distinguished from the Jura by the well-marked division into two longitudinal zones of elevation—one turned towards the Atlantic, in which the form of parallel chains predominates; the other turned towards the interior, composed of elevated and continuous plateaux. Occasionally minor chains very little elevated from the base wrinkle the surface of the tablelands.

This group of parallel chains may be arranged in three divisions, the northern being composed of Devonian and Silurian rocks, which 400 feet of water would separate from the American continent.

The central is the region of folded chains, with elevations of from 800 and 1500 to 2500 feet, gradually increasing in elevation towards the south and becoming more indented. The southern division, from the New River to the extremity of the system, is remarkable for the diversity of its physical structure and its general altitude. In the Blue Ridge its more elevated groups attain from 5000 to 5900 feet.

This very clear description by Prof. Guyot will enable us to picture the external physical features of these remarkable mountains. In another chapter we shall discuss more particularly the geological features of the system.

The map, Plate VIII., and section, Plate IX., will enable the reader to follow the foregoing descriptions and reasoning.

The Rocky-Mountain System.

The Rocky-Mountain system does not possess the simplicity of structure and symmetry found in the Appalachian chains. It also has not been so thoroughly worked out in all its geological aspects, yet sufficient has been done by a

PLATE VIII.

Map of the Appalachian region, constructed from the one prepared by Mr. W. J. McGee for the U.S. Geological Survey (1880), "Exhibiting the present status of knowledge relating to the areal distribution of Geologic groups."

The references to the formations are given on the Map itself. The system of shading adopted is on the same principle as Plate VII., the Archæan being the lightest and the Tertiary the darkest.

It exhibits the direction of the Appalachian Ranges by the strike of the strata, and enables us to realize the enormous amount of denudation that has taken place since their upheaval, as explained on p. 34.

The dotted line, A B, is the line of section given in Plate IX. This section is a copy of one prepared by H. D. Rogers, and published in 1857. It gives a good idea of the system of folds constituting the Appalachians as interpreted by him. The names of the rock-systems are rather fanciful, so I have appended the equivalent terms in common use.

PLATE IX.

Section across Pennsylvania and the Appalachians from the New York State Line at Connewago Creek, Warren Co., passing through Lewistown to the Maryland Line in York Co. A to B in Map of the Appalachian region (Plate VIII., p. 41), a distance of about 200 miles. (H. D. Rogers, 1st Geological Survey of Pennsylvania, 1857.)

A. Primal Slates, altered and crystalline.
B. Primal Slate and Sandstone.
C. Primal.
D. Auroral. } Lower Silurian.
E. Matinal.
F. Levant.
G. Surgent. } Upper Silurian.
H. Meridian.
I. Cadent.
J. Vergent. } Devonian.
K. Ponent.
L. Vespertine. Lower Carboniferous.
M. Mesozoic Red Shale and Sandstones.

Explanation of Terms, arranged in ascending order.

"*Primal*" includes the Crystalline Schists or Azoic Group, Conglomerate: Older Slate; Potsdam Sandstone: Upper Slate.

"*Auroral*" includes the Calciferous Sandstone of New York, and Chazy and Black River Limestone.

"*Matinal*" includes Trenton Limestone, Utica Slate, Hudson River Slates.

"*Levant*" includes Oneida Conglomerate, Medina Sandstone.

"*Surgent*" includes Clinton Group.

"*Meridian*" includes Upper Helderberg or Corniferous Limestone.

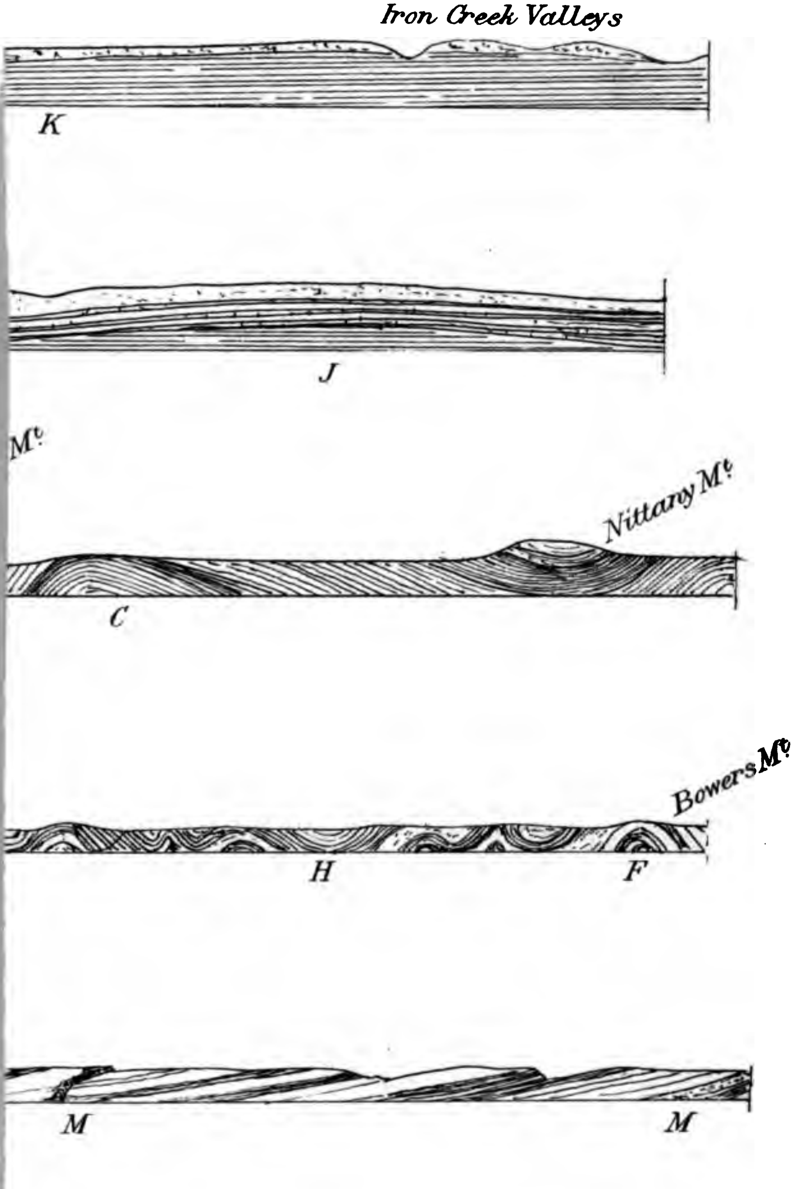
"*Cadent*" includes Marcellus Slate, Hamilton Group, and Genessee Slate.

"*Vergent*" includes Portage Flags, Chemung Group.

"*Ponent*" includes Catskill Group.

"*Vespertine*" consists of Conglomerate and Sandstone, and Carbonaceous Slates.

Plate IX.



Sprague & C° Photo-litho. London

numerous body of able State geologists, who have made mountain-structure a special study, to show how varied are the manifestations of the forces which cause the upheaval of mountain-ranges.

The dependence of this system of mountains, together with those of the Pacific-coast ranges, upon sedimentation is seen at a glance on reference to the map (Plate X.). From the Missouri river westward to the coast, commencing with the Cretaceous system which extends to Salt Lake, almost every formation is met with, from the Archæan to the Tertiary. The Cretaceous attains its greatest thickness in Wyoming, Utah, and Colorado, where it reaches 9000 feet or more. In these Rocky-Mountain territories it passes upward without interruption into a coal-bearing formation several thousand feet thick, on which the succeeding Tertiary strata lie unconformably *.

The Jurassic and Triassic beds are found in the Rocky-Mountain region; they are conformable, and there is often a difficulty in dividing them. They exist in the Black Hills in Dakota, and the Red Buttes in the North Platte. In the Elk Mountains of the western part of the Colorado territory, the upper parts of several of the peaks over 14,000 feet high consist of several thousand feet of Triassic or Triassic and Jurassic sandstones and marlytes, nearly horizontally stratified, overlying Carboniferous strata.

The high Wahsatch and Uinta Mountains, east of the Great Salt Lake, are also largely Triassic and Jurassic over Carboniferous, and so is part of the Humboldt Ranges west of this lake; on the Wahsatch the beds consist of sandstones and dolomitic limestones 1800 feet thick. The Triassic of the Sierra Nevada has been observed in California, according to Whitney, in El Dorado County at Spanish Flat, in Puma County, near Gifford's Ranch, &c.; also in Owen's

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* Dana, 'Manual of Geology,' 2nd ed. p. 454.

Valley along the western flanks of the Inyo White Mountains [*].

The following sketch by Prof. John J. Stevenson gives a good outline of the physical features of the Rocky Mountains[†]. From the Missouri river westwards the whole country gradually rises at an average grade of barely 10 feet to the mile, until west longitude 105° 30′ (approximately) is reached, when the Rocky Mountains rise abruptly from the plain. From this line the ranges extend to somewhat beyond west longitude 108°, when they rapidly fall off to the great plateau separating the Rocky-Mountain region from the broken ranges of Utah and Nevada.

The ranges comprising the great system under consideration appear to be in two series—the first comprising the two complex axes of elevation, the front or Eastern and the Sangre de Cristo, whose trend is from the north 10° west to north 30° west; while the second is made up of the San Juan, Los Piños, La Plata, and San Miguel, which have a trend of north 30° west, to north 45° west.

Each series shows a parallelism of its ranges, and the whole system terminates *en échelon* southwards, most of the axes ending within Colorado.

The observations of Dr. Newberry and Mr. Gilbert show that minor axes occur in New Mexico.

These are apparently independent of each other and of the main axes in Colorado, but it is by no means improbable that future examinations will disclose some more intimate relation than has been suspected. This range is composed of metamorphic rocks, which are badly fissured by dykes of lava. The schists are much torn and faulted, and side-throws of mineral veins are by no means uncommon.

In some of the cañons which cut deeply into the flanks of the mountains a compact granite, more or less syenitic, is seen, which seems to prevail along the median line of the axes, having been observed near the head of Clear Creek Cañon as well as in the walls of the amphitheatre containing Chicago Lake. The sedimentary rocks occur in "hog-backs" along the eastern base, and curve round the southern termination of the several axes. They pass round the Greenhorn Mountains into Huerfano Park, where they are more or less concealed by the great overflow of volcanic rocks.

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[*] Quoted from Dana, p. 406.

[†] See last two paragraphs in the description of Plate XI., p. 50.

The dips of the metamorphic rocks of this range are for the most part northerly, either north-west or north-east, and no satisfactory anticlinal or synclinal structure could be made out*.

Between the eastern range and the one next westwards, there occurs a series of Parks separated by outlying spurs from the mountains.

In Smith Park the Cretaceous rocks rest directly upon the metamorphic rocks, and are themselves more or less altered. In no locality were they seen resting upon any sedimentary rocks older than themselves.

The *Second* Range, which may be termed provisionally the *Sangre de Cristo* axis of elevation, is in the main almost parallel with the Eastern range, but is much more complex in its structure.

It is divided longitudinally by the Arkansas River, which, turning eastward, breaks through its eastern slope. Northward beyond our area, it is cut by the Grand River. In its northward extension, within our area it is known as the Blue River Range; further south, where it forms the western boundary of the South Park, it is the Park Range; in its southern extension it is called the Sangre de Cristo and Spanish range; while beyond our limits, to Santa Fé, where it ends, it bears several names.

On the eastern slope of the Park range the Palæozoic rocks reach quite the crest, and are traceable from the Sangre de

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* The Metamorphic Rocks are shown as Archæan in Mr. McGee's map.

Cristo to our northern line. Underlying them are metamorphic schists and gneisses, which are seen in the deep cañons along the eastern face, *while on the western slope they extend from the river's level almost to the crest*, and are exposed all the way from the South Arkansas to the mouth of the Tennessee Creek.

The high ridges of metamorphic rock thrust out from each side of the Arkansas gorge demonstrate the continuity of the whole, and give a satisfactory succession unbroken anywhere except by the cañon.

In the main portion of the second group no rocks occur of later date than the Carboniferous, which, with the underlying Silurian, may be traced along the eastern face to the Blue River, nor do any occur until we reach the ancient synclinal trough which lies between the second group and the next one westward. There the Cretaceous rocks are involved in the great fold exhibited near the head of Rock Creek.

The *Third* great axis or line of elevation is the *San Juan*, so named because in its southern prolongation it forms the Sierra *San Juan*. It reaches into New Mexico and ends not far from Abiquiu, somewhat further north than the termination of the Sangre de Cristo axis.

As already stated, the main axis is for the most part buried under a great mass of volcanic rocks, which conceals those of sedimentary origin. In Northern New Mexico the *western slope* is *bare for a number of miles*, and near Sierra Amarilla the exposures show very marked unconformity between the Carboniferous and the overlying rocks. The older formations are overlaid at a very high angle, while the Cretaceous and Triassic ?, which are conformable to each other, have a very small dip.

The next great axis is the *Los Piños*, and is in part the divide between the Rio de los Piños and the Rio Piedra.

The only rocks seriously involved in this anticlinal are the Carboniferous and probably the Silurian, though the latter were not satisfactorily recognized. On each side of the fold, which is not more than five or six miles wide, the Cretaceous rocks are seen forming mesas and dipping only two or three degrees.

The next axis, termed *La Plata* by Dr. Newberry, forms in part the divide between the Rio de la Plata and Rio de las Animas. The only rocks involved are the Palæozoic, against which the Triassic and Cretaceous abut at an angle of barely 2°. This anticlinal, as well as the Los Piños, has been much broken by eruptions of volcanic rocks, which in many places have overflowed and formed a thick cap on the hills.

In general, respecting the dips it may be said that the prevailing direction is east-north-east and west-south-west, and the western dips are for the most part somewhat steeper than the eastern. The most extensive faults are on the *easterly slope and cross the easterly dips*. The most marked effect of the convulsions occurs on the easterly lines, the first and second axes, which are characterized by extensive faults and sharp dips. Crossing westwards or south-westwards, the dip diminishes in steepness, until in the *La Plata* they are comparatively slight*.

Prof. John Stevenson, to whose work I am indebted for the preceding description, sums as as follows †:—*The first great epoch of accelerated disturbance in the Rocky-Mountain region resulting in permanent elevation of the surface, was synchronous with that during which the Appalachian chain was completed.*

"The Rocky-Mountain system then is the result of four especially marked upheavals—the first at the close of the Carboniferous, the second at the close of the Trias, the third at the close of the Cretaceous, and the fourth during the Tertiary. Of these the first and third were the most general in their effects."

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* "Structure and Age of the Rocky-Mountain System," "Geology of a portion of Colorado examined in 1873." Report of Geographical and Geological Surveys west of the 100th Meridian, pp. 488–498; vol. iii., Geology, 1875.

† Ibid. p. 499.

It will be well to give here Mr. Stevenson's description of the adjoining areas of North Central New Mexico and South Central Colorado*. "This district includes portions of two great drainage areas, that of the Arkansas and that of the Rio Grande, and lies wholly east from the continental divide.

"The divide between the area of the Rio Grande and that of the Arkansas does not coincide wholly with the ranges designated on the map as the Culebra Mora and Las Vegas, for in several instances streams break through these mountains, and the divide is found as often in the lower as in the higher ridges.

"The Culebra axis enters the district from the north, and is continuous southwards to Bernal Mesa, at the extreme southern border of the area examined. Its course is shown by the Archæan core of the Culebra, Taos, Mora, and Las Vegas Ranges.

"The Cimmaron axis may be regarded as beginning near the Spanish Peaks at the north, and extending southward to very near latitude 35° 30′ in New Mexico. It is divided into the *Stonewall* and the *Anticlinal*, which require separate consideration.

"The Coyote Synclinal.—This trough lies between the Cimmaron and Culebra-Mora axis. The expansion of the Mora Archæan thrusts the Carboniferous area eastwards, so that it is followed by Coyote Creek from the head of the stream to Coyote.

"The Cimmaron axis becomes very strong between Sapello and Gallinas Creeks, and the Archæan rocks form bold hills for several miles north from the latter creek; while they are shown also in the deep Cañon by *which the creek crosses the axis*.

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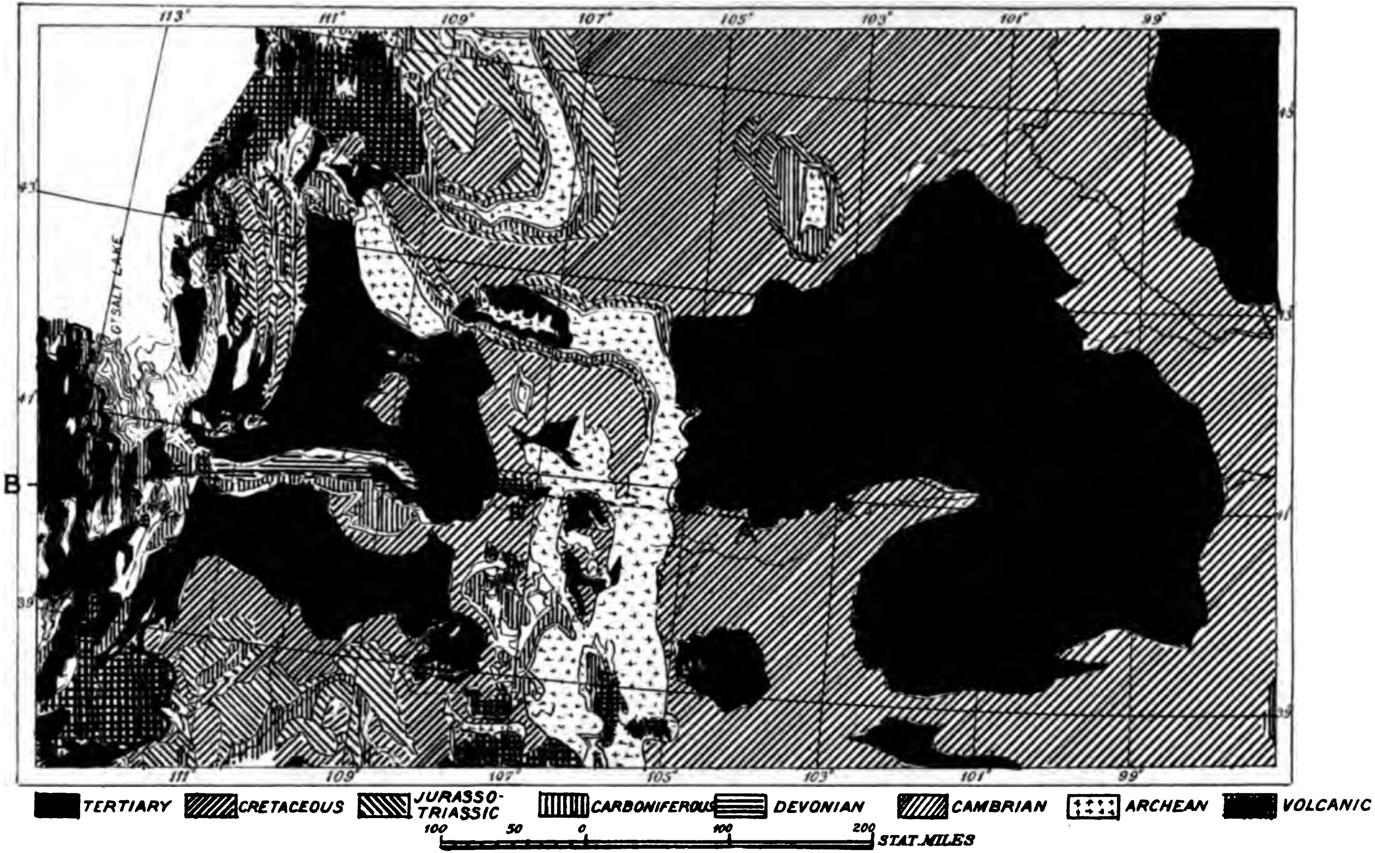
* Survey west of the 100th Meridian, vol. iii., Supplement. Quoted in abstract.

Plate X



MELLARD READE'S ORIGIN. OF MOUNTAIN RANGES.

Sprigg & C° Photo-litho. London

PLATE X.

Geological Map, showing part of the Rocky-Mountain Region and the Plateau System of Colorado, constructed from the map by Mr. W. J. McGee before referred to, showing the areal distribution of Geologic groups in the United States (1884). The shading is on the same system as maps, Plates VII. and VIII., the Tertiary beds being shown in black, the Archæan in white, with intermediate shades for the intervening formations. A comparison of this with the map of the Appalachian Region (Plate VIII.) will show how the Palæozoics of the Rockies, which were plicated synchronously with the Appalachian Ranges, were afterwards buried under great masses of sediment, which extended over an immense area beyond the immediate region of the Rocky Mountains, since which the whole have been flexed and upheaved in a complex manner, and denuded as explained in the text.

PLATE XI.

Sections through the Rocky-Mountain Region westwards.

Parts of Section from Longitude 104° to Longitude 120°, in the direction of line AB in Map, Plate X.

The Sections, Fig. 1 (1 to 3) are continuous.

Sections Figs. 2, 3, 4 are in the same line, but discontinuous, having intervals equal to the length of each section between them. To better identify the positions of the sections, I have marked the degrees of Longitude at the foot of each section.

The Sections are selected (with a view to exhibiting the characteristic structure of the region) from the Atlas accompanying the Report of the Geological Exploration of the Fortieth Parallel, by Clarence King, Geologist-in-charge (1876), referred to in the text.

The original sections are coloured. I have substituted line-shading and lettering to distinguish the Geological Formations.

My object in the system of shading adopted has been to develop the structure to the eye. For simplicity I have grouped the various beds together under the following reference letters:—

A. Tertiary.
B. Cretaceous.
C. Jurasso-Triassic.
D. Carboniferous.
E. Devonian.
F. Silurian.
G. Cambrian.
H. Archæan.

The Sections proceed from left to right in the order of the numbers at the termination of each Section.

The district examined by Prof. Stevenson in 1873, and described in pages 44 to 47, lies to the south of this line of section, or from 39° 45′ north latitude to the southern boundary of Colorado, a distance of 190 miles, and between the meridians 105° and 107° west from Greenwich, or about 106 miles. It exhibits "the grandest development of the Rocky Mountains to be found within the United States. The ranges are more massive, more sharply defined; and the average elevation is much greater than in any other portion of the Chain."

The Spanish Ranges described in pages 49 and 51 "are virtually a continuation of the Sangre de Cristo Range of Southern Colorado, terminating northwards in N. latitude 35° 20′."

"The intimate relation existing between the ranges is such that there seems no room for doubting that in their present shape they are synchronous. The last great period of upheaval was later than the close of the Laramie, for the Laramie rocks cross the Cimmaron axis at Poñil Pass, and traces of them remain in the Moreno valley near its northern termination, and much prior to the outpouring of the trachytes; for the line of contact between the Archæan and the last overflow in Cimmaron Cañon is an almost horizontal plane, showing that erosion had been long at work before the lavas overspread that region."

Mr. Stevenson observes that there are enormous conglomerates at the base of the Carboniferous along the Culebra and Taos ranges, as well as for miles along the Mora range. At nearly all the localities where the full succession is shown, the whole series seems to be conformable.

The dips of the Archæan rocks are much confused, and the distortion in most localities is so great that neither the succession of the strata nor the general structure could be made out during the brief examinations. Positive proof of nonconformity to the overlying Carboniferous is not easily obtained; usually the disturbance near the junction of the two series is very violent, and the rate of dip changes greatly within a short distance, sometimes becoming even reversed.

As the Cimmaron Range was formed at the close of the Cretaceous, erosion must have been at work with great energy during the Eocene, for the Archæan crust was reduced to a plateau prior to the trachyte overflow which covered this range from Old Baldy southward to Rayado Creek.

A thick deposit of alluvium crowded with boulders of Archæan rocks, evidently transported from the mountains of the west, underlies the basalt on this mesa. During the early Pliocene the basalts were poured out, covering the mesas, flowing down to the plains, and filling the cañons, so that the aspect of the region was wholly changed. The erosion since that time has been little less extensive than that performed during the Eocene and Miocene, though it has been confined very largely to the reopening of old channels. But the basalt plate has been removed from the plain bordering on the Upper Canadian*.

The Geological Map of the region of the Bow and Belly rivers, prepared by Dr. George M. Dawson †, shows the extension of the Rocky-Mountain system into Canada beyond the 51st parallel. There are no exposures of Archæans in the area shown on the map. The Cretaceous strata of the Foot Hills, extending from the United-States boundary to the north of the map and between the 113th and 115th meridians, are much folded and disturbed. The Porcupine Hills, composed of Laramie beds, occupy a synclinal trough ‡. The ridges of the Livingstone Range and the Rocky Mountains are composed of Palæozoic strata protruding through the Cretaceous.

The Cretaceous and Laramie, as shown in the section referred to, are folded, in some cases vertically, and planed off on the edges by denudation. Dr. Dawson says that "the ridges, with the strike of the rocks which they indicate, show a nearly complete parallelism with the base of the Palæozoic rocks of the mountains, and follow it in its light sinuosities. Long ridges, either covered with vegetation or having rocky summits formed by the outcrop of the harder sandstones, alternate with parallel valleys in which streams flow, while the rivers which have their sources in the mountains have cut their channels across at right angles"§. The report on this interesting region is well worthy of study.

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* Report upon the Geological examinations in Southern Colorado and Northern New Mexico during the years 1878–79, by John J. Stevenson: U. S. Geol. Survey west of the 100° Meridian. Vol. iii. Supplement.

† Geological Survey of Canada: Report of Progress, 1882–84.

‡ Ibid.; see section, p. 106 C.

§ Ibid. p. 11 C.

Mr. H. Bauerman, in a Report on the Geology of the Country near the 49th parallel of North Latitude west of the Rocky Mountains *, shows that the Palæozoics constitute the mass of the Rocky-Mountain region from the Saskatchewan river to the Mooyie river. Westward of these come gneissic rocks and granite, then Palæozoic and Archæan, and finally, east of the Fraser river, Cretaceous rocks enfolded in a synclinal.

The Basin-Range System.

Mr. G. K. Gilbert, in his valuable Report on the 'Geology of portions of Nevada, Utah, California, and Arizona,' gives the following description of the Basin-Range System.

"Throughout South-western Arizona the ranges consist of highly crystalline schists, in which no fossils have been found, and against these no beds are found to be of greater determined age than the Quaternary gravels. A few of them, which are adjacent to the Plateau system, are demonstrated to have been first upheaved at some time anterior to the Carboniferous, and again at some time subsequent to the Carboniferous. Further north, in Southern Nevada and adjacent portions of Utah and California, Silurian and Carboniferous strata have been identified at numerous points in the upheaved masses, and it is presumable that their principal elevation was coeval with that of the first and chief elevation of the Wahsatch Mountains and the Sierra Nevada, proved by Whitney and King to have occurred at the close of the Jurassic period"†. (Geol. Exploration 40th Parallel, vol. iii. p. 3.) "There is further evidence on the borders between the Basin-Range System and the plateau in Utah, that disturbances acting along the original line of Jurassic elevation have occurred later than the Eocene Tertiary, but of the geographical limits among the ranges of these movements little can be predicted from the stratigraphical data now at hand" (p. 24).

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* Geol. Survey of Canada: Report of Progress, 1882–84, pp. 5 B–42 A.

† Prof. Jules Marcou considers that the Sierra Nevada are of Azoic or ante Primordial age ("Géologie de la Californie," Bull. de la Soc. Géologique de France, 1883).

The Basin-Range area in its longer axes is meridional, and its width where best known is from 225 to 500 miles. On the 40th parallel it extends from the Sierra Nevada eastwards to the Wahsatch Range, which latter it includes. South of this line the Sierra Nevada may be regarded as its western limit, and on the east it is bounded with less regular outline by the Colorado Plateau System. "The ridges are composed of, first sedimentary strata, in part unaltered and in part subjected to various degrees of metamorphism; second, granite and cognate rocks; and third, volcanic rocks. The lines of structure are in general parallel in each range to the trend of the range. The granite occupies various positions. Often it is the nucleus of the range against which the inclined strata rest. Elsewhere it appears in dykes traversing either sedimentary rocks or other granites. While the ranges are locally parallel, there is considerable change of direction in the system as a whole. The volcanic rocks are seen to be of more recent date, since they overlie both granites and sedimentary rocks, and are found as dykes intersecting them."

Structure of Ridges.—"In the great majority of the ranges I have just described, and in an equally large proportion of others, in regard to which my observations were too cursory to warrant individual mention in this connexion, the best exhibit in cross section but a single direction of dip. Either the strata in a single body incline from the crest to the base of the range, or they are divided by a system of faults, trending parallel to the range, into several bodies, which dip in one common direction. In these cases the ranges may be called simple and compound monoclinals. Next in frequency are sections in which there appear at the base of the monoclinal escarpment strata dipping in the opposite direction.

"Pure anticlinals are exceedingly rare, but in a number of instances greatly shattered and dislocated rock-masses assume a quasi-anticlinal form.

"It is impossible, by any hypothetical denudation, to formulate the basin-ranges as remnants of a system of anticlinal and synclinal folds. The movements of the strata by which the ridges have been produced have been in chief part vertical along planes of fracture, and have not involved great horizontal compression."*

Mr. Gilbert considers the same forces acting over large areas have produced both the Basin-Range System and the Plateau System.

The Three Geological Provinces.

It will enable us to form a better idea of the relations of the mountain systems already described, if we study the following description by Capt. C. E. Dutton, who has done such important and suggestive work in Utah †.

"For convenience of geological discussion Prof. Powell has divided that belt of country which lies between Denver City and the Pacific, and between the 34th and the 43rd parallels, into provinces, each of which, as far as known, possesses structural and topographical features which distinguish it from the others ‡. The easternmost division he has named the Park Province. It is characterized by lofty mountain-ranges, consisting of granitoid and metamorphic rocks, pushed upward and protruded through sedimentary strata, the latter being turned upwards upon the flanks of the ranges, and their edges truncated by erosion. The general transverse section presented by these ranges, on the assumption that the sedimentaries prior to the uplifting extended over their present *loci*, is that of a broad and extensive anticlinal sometimes profoundly faulted parallel to the trend, the sedimentary strata which may once have existed being removed by erosion. The intervening valleys still retain the Sedimentary series, including the Tertiary beds. This form of mountain structure, with its resulting topographical features, gradually passes as we proceed westward into another type, arising from the decreasing frequency of the greater displacements or differential vertical movements of the earth's surface; but such movements as have occurred have been vast in extent and involve greater masses, though the displacements have been fewer in number.

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* Report upon Surveys west of the 100° Meridian, vol. iii. Geology, 1875: Part 1. Geology of portions of Nevada, Utah, California, and Arizona, by G. K. Gilbert, A.M.

† "Report on the Geology of the High Plateaus of Utah," U. S. Geographical and Geological Survey of the Rocky Mountain Range, 1880, pp. 5–7.

‡ "Report on the Geology of the Eastern portion of the Uinta Mountains, U. S. Geol. and Geogr. Survey of the Territories, 1876, chap. i."

"Great blocks of country have been lifted with a singular uniformity with comparatively little flexing, and with little disarrangement, except at the fault-planes which bound the several blocks.

"These divisional lines are sometimes sharp trenchant faults, sometimes that peculiar form of displacement to which Messrs. Powell and Gilbert have given the name of monoclinal flexures, and a fault or series of faults with all shades of relative emphasis. If we look solely at the amount of energy displayed in the vertical differential movements, we shall probably reach the conviction that it does not fall much, if any, below that required to build the most imposing mountain-ranges; yet within the limits of any one of the great blocks into which this country has been divided, the strata have preserved their original attitudes with a singularly small amount of warping, flexing, and comminution.

"Sometimes the blocks are slightly tilted, causing a slight dip, and in the immediate neighbourhood of a great dislocation a single flexure of the beds is usually seen; but on the whole the amount of bending and undulation is very small. This small amount of departure from horizontality of the beds as they now lie has played its part in the determination of the topographical features as they appear in the landscape, and justifies the name which has been applied to it with one accord by all observers, THE PLATEAU COUNTRY.

"West of this province lies a third one—the Great Basin. Its topography and structure are characterized by jagged ranges of mountains, ordinarily of very moderate length and separated by wide intervals of barren plains. These ranges are usually monoclinal ridges produced by the uptilting of the strata along one side of a fault. Sometimes the faults are multiple; that is, consist of a series of parallel faults, the intervening blocks being careened in the same manner and direction. This repetitive faulting is of frequent occurrence. Other modifications, and even different types of structure, are presented; but there is throughout the Great Basin a striking predominance of monoclinal ridges, in which one side of a range slopes with the dip of the strata, while the other slopes lie across the upturned edges. The forms impressed upon these masses by erosion are rugged, bristling, and sierra-like, and their peculiarities are aggravated by the fact that before these 'mountains were brought forth' the platform of the country from which they arose had been plicated, and the plication planed down again by erosion. The Basin area is the oldest of the West, its final emergence being of older date than the Jurassic, and most probably as ancient as the close of the Carboniferous."

The Cretaceous-Eocene strata forming the main mass out of which the Plateau Province was blocked in the way so graphically described by Captain Dutton, is with few exceptions conformable from base to summit. It is from 6000 to 15,000 feet thick, and covers more than 100,000 square miles.

The whole series abounds in coal and carbonaceous shales, and remains of land-plants are abundant even when carbonaceous matter is absent.

Captain Dutton considers that the heaviest masses of the Cretaceous-Eocene were derived from the Uinta and Wahsatch ranges, pointing out that from the former 30,000 feet* of strata have been removed since their emergence and from the latter much more, while the Great Basin suffered degradation to the extent of several thousand feet.

Then a new era of erosion began, resulting in the destruction and dissipation of these great bodies of sediment which had been gathered and stratified during Mesozoic and Eocene times.

From the inception of the process the drainage system has been the plexus of streams which unite in the Colorado River. Through this trough the waste of the land has been carried into the Pacific. The river is older than the structural features of the country. Since it began to run, mountains and plateaus have risen across its track and those of its tributaries, and the present summits mark less than half the total uplifts †. The average denudation of the Plateau Province since the closing periods of the local Eocene are approximately estimated by Captain Dutton at 6000 feet, the amount varying enormously, being in some localities practically nothing, in others nearly 12,000 feet. It is at a minimum in the High Plateaus, where the average denudation will fall below 1000 feet in the sedimentary beds. Enormous floods of volcanic emanations have protected them, and borne the brunt of the erosion, giving rise to local accumulations of subaerial conglomerates in all the valleys and plains surrounding the volcanic areas ‡.

The High Plateaus are remnants of great masses of Tertiary and Cretaceous strata left by the immense denudation of the Plateau Province. Not only the Eocene and Cretaceous, but the Jurassic, which has great importance and bulk in the northern and north-western portions of the province, has been enormously eroded.

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* This was determined by Powell, as we shall see when we come to consider the Uinta range separately in fuller detail.

† High Plateaus of Utah, p. 16. ‡ Ibid. p. 23.

The Great Basin lies at a lower mean level than the Plateau country, and here the predominance of the High Plateaus is due to a different cause.

The difference of altitude is due to displacement and not erosion (uplifting, Captain Dutton thinks). Those cliffs, which had their origin in displacement, with few exceptions face westwards. The country to the east of them, and also the belt of country which they occupy, has been elevated from 5000 to 6500 above the country to the west of them. "The passage from west to east across the belt of country, which may be called the border-land between the two provinces, discloses a succession of faults and monoclinal flexures which are obvious results of such a displacement."

I have dwelt at considerable length on the Geology of the western side of the United States, because in that region are to be found several types of mountains in contiguity, and because it is here that some of the battles on the origin of mountain-ranges have been fought. Men of such lively intelligence as the eminent officers of the United States Geological Survey could not be brought in contact with mountain phenomena on so large a scale, and possessing such distinct and peculiar features, without formulating some theory of their origin.

To these and the views of Profs. Le Conte and Dana I shall have occasion to refer hereafter. It will be well now to take a glance at mountains in other parts of the world, and the excellent 'Handbook of the Geology of India,' by Messrs. Medlicott and Blanford, will enable us to do this. Whenever it is possible I will, as in the preceding pages, give the description in the author's words, as I wish the reader to form his conception of the phenomena described through the eyes of those who have seen them, rather than after filtration through my mind.

Geology of India and Structure of the Himalayas.

Peninsular India.

Messrs. Medlicott and Blanford divide India into two Geological provinces, viz. the Peninsular and Extra-Peninsular areas, the Indo-Gangetic plain lying between them. This plain is an immense expanse of flat country stretching from sea to sea, entirely composed of alluvial deposits of very late geological age, and dividing the hilly ground of the Peninsula from the various mountain- and hill-ranges ot Sind, the Punjab, the Himalayas, Assam, and Burma. The Geology of these regions is widely different, and even in the character of the surface there is a marked contrast due to the great effects produced by disturbance in late geological times throughout the Extra-Peninsular region—an effect culminating in the elevation of the Himalayan chain; whilst in the Peninsula there appears to have been singularly little contortion or alteration of the strata after a very early period.

The Vindhyans of Bundelkhand and Central India are certainly not newer than Lower Palæozoic; yet they are nearly horizontal throughout the greater part of their area; and they are far less tilted and folded than the Pliocene Siwaliks along the base of the Himalayas, and of the Punjab and Sind mountains on the opposite side of the Indo-Gangetic plain*.

The peculiarity of all the main dividing ranges of India is, that they are merely plateaus or portions of plateaus that have escaped denudation. There is not throughout the length and breadth of the peninsula, with the possible exception of the Arvali, a single great range of mountains that coincides with a definite axis of elevation; not one, with the exception quoted, is along an anticlinal or synclinal ridge. Peninsular India is in fact a tableland, worn away by subaerial denudations, and, perhaps to a minor extent, on its margins by the sea; and the mountain-chains are merely the dividing lines left undenuded between different drainage areas (differentially denuded?).

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* Vol. i. p. iii.

"Where the rocks are so ancient as those are that form all the southern portion of the Sahyádri, it is almost impossible to say how far the original direction of the range is due to axes of disturbance; but the fact that all the principal elevations, such as the Nilgiris, Palnés, &c., some peaks of which rise to over 8000 feet, are plateaus and not ridges, tends to show that denudation has played the principal share in determining their contour."*

There is a remarkable absence in the Indian Peninsula of any evidence of disturbance in late geological times.

The Arvali differs from the other great ranges of India in being entirely composed of disturbed rocks, with the axes of disturbance corresponding with the direction of the chain.

The formations found in the Arvali range belong to the transition rocks, and are of great antiquity; for the most part they are much altered; they are quite unfossiliferous, and there is evidence which renders it probable that the elevation of the range dates from a period anterior to the deposition of the Vindhyan rocks, themselves of unknown age, but almost certainly not of later date than older Palæozoic; whilst the fact that these Vindhyan rocks are found almost horizontal in the neighbourhood of the Arvali range, on both sides of the chain, shows that here as elsewhere in the Peninsula the forces which have affected the non-peninsular area in later geological epochs have not been felt.†

Mountain-Ranges of the Extra-Peninsular Area.

Passing to the other side of the Indo-Gangetic plain, no matter whether the region be reached to the westward in Sind and the Punjab, to the northward in the Himalayas, or to the eastward in Chittagong and Burma, the mountain-ranges, with the exception of a portion of the Assam range, are everywhere composed of disturbed and contorted beds, and the disturbance has invariably affected rocks of late geological age. The amount of alteration may be small or great: the hills may consist of simple anticlinal folds, as in Sind, or of the most complicated inversions, as in parts of the Himalayas; the strike of the bedding may vary from east and west to north and south; but two characters are constant, great disturbance affecting all the formations, and the coincidence of the direction of the ranges with synclinal and anticlinal axes.*

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* Vol. i. p. v.

† Vol. i. p. vii.

Sind and Western Punjab.—In physical characters, as in geology, there is to some extent a passage between the two great and contrasting regions in the Western Indian provinces of Guzerat, Kattywar, and Cutch. The rocks of the Eastern Salt-Range in the Punjab differ from those of the western extremity, and the former approximate to the Peninsular type.

Passing on to the Extra-Peninsular area, and commencing on the west in Sind, there are to the westward of the Indus several ranges having a general north and south direction; of these the most important is the Khirthar, forming the western boundary of Upper Sind. But little is really known of the geography west of the frontier.

The next range to the northward, the Sulemán, forming the boundary of the Punjab, is again a north and south range like the Khirthar.

The Northern Punjab is traversed by a series of ranges having a general east and west strike, but being frequently curved, the curvature being greatest in the Salt-Range, the most southern of all, and its continuation west of the Indus; whilst the ranges near Pesháwar and Attock are more nearly east and west.

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* Vol. i. p. vii.

Himalaya.—"The Himalayas may be considered as extending from the Indus to the Brahmaputra; these two great rivers between them almost encircling the mountain zone of Northern India. Of the great mountain zone thus defined, the western portion alone is well known; even here the geology requires much additional study.

"The Himalaya, considered as a whole, forms a curved belt of mountains with their convexity to the southward, running nearly from north-west to south-east to the westward, and from west to east to the eastward, the eastern extremity striking north of east.

"But besides composing a great mountain-chain or series of chains, the Himalayas form the southern scarp of the Tibetan plateau, a tract of highland from about 12,000 to 16,000 feet above the sea. The northern scarp of this plateau is formed by the Kuenlun, overlying the lower plains of Eastern Turkestan and the Gobi desert." *

"The western terminal portion of the Himalayan chain—the only part as already stated that has been accurately mapped—comprises a number of great ranges, the majority of which have no settled appellations, but are commonly known by the terms applied to the passes through them, or by the names of the districts traversed. The principal of these ranges are the Mustágh, Ladák, Zánskár or Báralácha, and the Pir Panjál. The Mustágh forms the northern watershed of the Indus and its tributary the Shayok, and separates their drainage area from the upper waters of the Yárkand River. To the north-west the Mustágh range appears to curve round into the northeast-southwest chain of the Hindu Kush, and is of great height; its culminating peak, the nameless summit known on the Great Trigonometrical Survey maps as K2, rising to an elevation of 28,278 feet, and being only second to Mount Everest. The Ladák range intervenes between the Indus and the Shayok. The Zánskár range divides the Upper Indus from the Jhelum and Chináb; the north-western continuation forming the northern boundary of the Kashmir Valley and terminating in the peak of Nanda Parbat. The Pir Pánjal divides the Kashmir Valley, drained by the Upper Jhelum, from the plains of the Punjab. All these ranges have a north-west to south-east direction; and to the westward there is a singularly abrupt change in the strike, as in the instance already mentioned of the angle formed by the Mustágh range and the Hindu Kush.

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* Vol. i. p. viii.

" It is doubtful whether any of the ranges already noted in the terminal area should be considered the prolongation of the main Himalayan axis, although, if any be a real continuation of the Himalayas proper, it is either the Pir Panjál or the Zanskár range. The main range of the Himalayas appears more probably, so far as geological structure affords a clue, to commence to the westward in the Dhauladhár, a minor ridge rising from the banks of the Rávi close to Dalhousie, and extending to the east-southeast, till it rises in the main survey range of the North-west Himalayas.

"Many geographers distinguish two parallel ranges from the neighbourhood of Simla to the eastward—the Snowy range proper, formed of the highest peaks, and a more northern ridge forming the watershed between the Tibetan plain and the rivers running to the plains of India. Others consider the latter to be the true Himalayan range, and look on the higher peaks as belonging to the spurs between the rivers flowing from that range. It is certain that the great peaks such as Nanda Devi (25,700 feet), Dhaulagiri (26,826 feet), Mount Everest (29,002 feet), Kinchinjinga (28,156 feet), Chumalari (23,929 feet), &c., are separated from each other by deep valleys through which flow streams coming from the northern range, and that although the peaks of the latter are inferior in elevation, the passes by which it is traversed are much higher; but it has not yet been ascertained whether the great peaks are on the strike of any continuous band of rock, or whether they merely consist of hard nuclei left undenuded.

"Along the southern base of the Himalayas, and parallel with the general direction of the mountains, a series of comparatively low ridges extends, formed of Tertiary rocks, and separated from each other, or from the rocks of the main ridge, by valleys called dúns. These fringing ranges of the later formations are known generally as the Sub-Himalayas, the most important being the Siwalik Hills, a term especially applied to the hills south of the Deyra Dún, but frequently applied in a wider sense than its original application. To the eastward the Sub-Himalayan ranges are less conspicuous than to the westward; but they are only locally wanting altogether, and are to be traced almost throughout the Himalayan border, from the Punjab to Upper Assam." *

Geological Formations.

In the Peninsular Area the total thickness of rocks is estimated at over 75,000 feet, of which 34,000 are Azoic, 13,000 Palæozoic, 26,000 Mesozoic, and 2,700 Cainozoic.

There is throughout a remarkable deficiency of fossiliferous marine rocks, the few that occur being almost exclusively found in the neighbourhood of the present coast, or else in the desert between the Arvali chain and the River Indus, and none are older than the Jurassic.

In the Extra-Peninsular areas, owing to difficulties created by the separation of the different tracts of Extra-Peninsular India comprised in British Territory by regions such as Nepaul and Afghanistan, entirely inaccessible to Europeans, the correlation of the various formations in the Extra-Peninsular region with one another is more imperfect than in the Peninsular area.

With the exception of Sind, there are but two localities in

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* Vol. i. p. x.

Extra-Peninsular India where peninsular rocks are found. One of these is at the base of the Himalayas, in Sikkim and Bhután, where fossiliferous Damúda beds occur. The other is in the Assam hills, where representatives of the metamorphic and Cretaceous (marine) rocks of the Peninsula, and in all probability of the transition beds of the Rájmahál traps are found *.

Representatives of the Pliocene, Miocene, Eocene, Cretaceous, Jurassic, Triassic, Permian, Carboniferous, and Silurian are found in the Extra-Peninsular area, and below them in places gneiss of unknown age, and the central gneiss of the Himalayas.

The thickness of the formations has only been determined in a few instances. The amounts are very great, the Tertiary rocks alone attaining a vertical development in places in Sind of nearly 30,000 feet.

SOUTH AMERICA.

The Andes.

This system of mountains, in some respects, perhaps, the most remarkable in the world, is, compared with the preceding systems, structurally very imperfectly known. From this reason I shall not have much to say with regard to these great ranges, but it will perhaps help our purpose if I give a slight outline of what is known of them.

Physical Aspect.—The Andes mountain-system in the larger part of its extent consists of two parallel chains, whose crests are separated by broad plateau-like valleys from 20 to 60 miles wide, and from 8000 to 13,000 feet high. Near the northern termination there are three diverging chains instead of two, and near the southern there is but one.

Numerous cross swells or mountain knobs connect the ranges separating the high intervening valley into a number

* Vol. i. p. xv.

of distinct basins. The broadest and highest of these is the Plateau of Bolivia, opposite the Gulf of Arica, the great indentation of the Pacific coast.

The altitude of the Andes increases from the Isthmus of Panama southward to the plateau of Bolivia, where the crests rise to 16,000 feet, and the highest peaks are from 20,000 to 25,000 feet in elevation. The breadth of the system is only from 200 to 300 miles. The slopes are abrupt, and deeply cut by transverse valleys. No longitudinal valleys occur in the western slope, and but few in the eastern slope of the Central Andes.

The summit of the ranges is not a narrow sharp ridge, but is often a plateau-like expansion, sometimes several miles broad, from which numerous volcanic peaks rise abruptly *.

There are, therefore, several remarkable features possessed by this range—length, altitude, straightness of direction, narrowness, and the presence of volcanoes.

In 1846, Mr. Darwin published an account of the Geological structure of the Chilian Cordillera and the southern parts of South America †. Mr. Darwin's opportunities of geological surveying were only those given by a few traverses of these mountains. With his usual insight he probably made better use of his time than any one else could have done in his day. The knowledge of mountain-structure was unfortunately at that time not sufficiently advanced to enable him to formulate his observations in a way to satisfy the modern student of mountain-geology; but his remarks and generalizations display so much acuteness that they are well worthy of study.

Mr. Darwin shows that from Tres Montes to Copiapo, and, as he believed, much further, the shores of the Pacific are composed of metamorphic schists, plutonic rocks, and more or less altered clay-slate. On the floor of the ocean so con-

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* Physical Geography, by Arnold Guyot.

† Reprinted in 'Geological Observations,' 1876.

stituted, in profoundly deep water, vast streams of various purplish clay-stone and greenstone porphyries were poured forth, together with great alternating piles of angular and rounded fragments of similar rocks ejected from submarine craters. At the period when these ceased to be erupted, the great pile of strata which Mr. Darwin called the Gypseous formation was deposited, and feldspathic lavas, together with other singular volcanic rocks, were occasionally poured forth.

At the commencement of the Gypseous period, the bottom of the sea seems to have been peopled with shells, not many in kind, but abounding in individuals. These shells, in the opinion of all the paleontologists who examined them, belong to the earliest part of the Cretaceous system, or what Mr. Darwin calls the Cretaceo-Oolitic. The strata in this formation are composed of black calcareous shaly rocks, of red and white, and sometimes siliceous sandstones, of coarse conglomerates, limestones, tuffs, dark mudstones, "pseudo-hornstones," vast beds of gypsum, and many other jaspery and scarcely describable varieties, which vary and replace each other in short horizontal distances, to an extent unequalled even in any Tertiary basin.

Mr. Darwin thinks that in some parts of the Cordillera the upper beds of the Gypseous formation lie unconformably on the lower beds, and the whole Gypseous formation, in parts, unconformably on the porphyritic conglomerate.

In Central Chile, after the deposition of a great thickness of the Gypseous strata, and after their upheaval by which the Cumbre and adjoining ranges were formed, a vast pile of tufaceous matter and submarine lava was accumulated where the Uspallata chain now stands.

We have evidence, then, of a second great period of subsidence, accompanied, as in the case of the Cretaceo-Oolitic strata, as shown by the vertical trees embedded in the strata, by local elevatory movements.

The ridges formed by the angularly upheaved strata are seldom of great length. The angular displacement has been much more violent in the central than in the exterior main lines, but it has likewise been violent in some of the minor lines of the extreme flanks. The violence has been very unequal in the same short lines, the crust having apparently tended to yield in certain parts along the lines of fissure. The andesitic rocks have in most cases been the last injected ones, and they probably form a continuous dome under this great range.

Mr. Darwin thinks that some of several parallel ridges composing the Cordillera were contemporaneously elevated and injected. In the case of the gigantic Portillo range, "we may feel certain" that a pre-existing granitic line was upraised at a period long subsequent to the upheavment of the parallel Peuquenes range, and that the Uspallata range was formed subsequently to the Cumbre chain.

The manner in which the various kinds of porphyries and andesites have been injected one into the other, and in which the infinitely numerous dykes of various compositions intersect each other, plainly show that the stratified crust has been stretched and has yielded many times over the same points.

Mr. Darwin also shows that elevatory movements have been taking place in the Andes over great areas even up to the present day.

"In South America everything has taken place on a grand scale, and all geological phenomena are in active operation. We know how violent at the present day the earthquakes are, we have seen how great an area is now rising, and the plains of tertiary origin are of vast dimensions." The areas of the basal metamorphic and plutonic rocks of the continent are likewise vast, and their plains of cleavage and foliation strike over surprisingly great spaces in uniform directions.

This grand range of the Cordillera, with its pinnacles rising here and there to 20,000 feet above the sea, has suffered both the most violent dislocations, and slow though grand upward and downward movements in mass.

The Cordillera, from Tierra del Fuego to Mexico, is penetrated by volcanic orifices, and those now in action are connected in great trains.

The permanence of volcanic action in this chain of mountains is also a striking fact, and it would appear that the Cordillera has been, probably with some quiescent periods, a source of volcanic matter from an epoch anterior to our Cretaceo-Oolitic formation to the present day.*

There is one weak point in this wonderfully graphic description of geological action and succession—it takes no account of lateral pressure. After what we now know of the Alps and similar systems, we should expect to find much of the strata folded, contorted, and involved; but Mr. Darwin appeared at the time fully possessed with the prevalent notion that all or nearly all was due to "vertical upheaval" and violent dislocation.

To make the sections accompanying his description physically intelligible and consistent, some system of anticlinal and synclinal folds seem required.

As they are shown, the ranges seem to consist of detached blocks of strata. Mr. Darwin's work was at the time a highly valuable contribution to the science of Geology, and much of its value still remains.

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* Geol. Obs. p. 602.

CHAPTER VI.

GENERAL REVIEW OF THE GEOLOGICAL EVIDENCE ASSOCIATING MOUNTAIN UPHEAVAL WITH PREVIOUS SEDIMENTATION.

THIS enquiry is essentially one in which the evidence sought for should be gleaned from an extensive field. The descriptions already given being largely in the words of the several authors quoted, necessarily contain a reflex of their individual views. This is, however, not without its advantages, as we are thereby enabled to more fully realize the reasons that have most influenced their conclusions. Facts and opinions, when placed in juxtaposition, often mutually explain each other as well as making them easier of assimilation.

A tendency, common to all minds, to look at facts through specially coloured media, is also more likely to be corrected.

North America.

The first important relation that arrests attention, is the dependence of the structure of the mountain-ranges on the actual thickness and nature of the sedimentary deposits which preceded their uplift, and out of which they are mainly formed. We see that the upraising and folding of the remarkable anticlinal chains of the Appalachians, as pointed out by Dana, was preceded by the quiet deposition of some 40,000 feet of sedimentary rocks extending in varying thickness over an immense area. Also, according to the United-States geologists, simultaneous uplifts occurred at the close of the Carboniferous in the district now the Western States and Territories of America, after the deposition of great masses of sediment and limestones. But upon these latter areas were subsequently deposited a vast series of strata ranging from the Trias to the end of the Tertiary.

According to Prof. Stevenson, movements of disturbance followed the Miocene period, but undoubtedly great earth-movements took place at the close of the Cretaceous and after the deposition of great volumes of sediment. Again, great but minor movements followed the Tertiary depositions, and have continued in a greater or less degree to the present time.

Not only is it true that a real connexion is thus traced between sedimentary deposition and orographic displacement, but the converse holds good even in the areas of the western states. Mr. Clarence King says—after describing the orography of the territories comprised in the survey of the 40th Parallel* :—" It is also a general law that those regions which experience elevation without local disturbance are the regions of relatively thin sediment superposed on a comparatively unaccidented Archæan foundation, whereas those which suffer the extremest plication are covered by the thickest deposits overlying and adjacent to the greatest Archæan mountain ranges."

It is unnecessary here to discuss the details of the successive elevatory movements to which the regions between the eastern slope of the Rocky Mountains and the Pacific have been from time to time subjected, or to what extent they are separate and distinct in time, or successive, or continuous developments of the same disturbing causes. I prefer, for the present, to confine my views to the broad and salient facts.

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* 'Geological Exploration of the 40th Parallel,' Systematic Geology, vol. i. p. 761. (1878).

South America.

If now we turn our eyes to the southern continent of America, we find that Mr. Darwin, forty years ago (an era in this department of geology), with his usual acumen, shadowed forth a somewhat similar set of geological conditions, commencing with the deposition of volcanic rocks upon a floor of gneiss and schist, and the subsequent deposit upon them of a great thickness of what he calls "Cretaceo-Oolitic" strata, and he points out that the Cordilleras have been the seat of volcanic action—perhaps with periods of quiescence—from their inception up to the present time. Here again we find that sedimentation precedes mountain-building, and not only so, but that the development of volcanic activity, as shown by the lava intercalated in the sedimentaries, does not necessarily mean the formation of mountains. In this case it was at first co-existent with great and extensive subsidence; that is, if we accept Darwin's views. Thus it is perhaps more strongly emphasized in the Andes than elsewhere that mountain-building cannot take place without a great previous laying down of rocks, whether composed of the ejectmenta of volcanoes, lava-flows, or ordinary sediment.

India.

What is known of the Geology of India tells us the same great truth in a most picturesque and striking manner. Here we have side by side two great and remarkable areas—the Peninsular and the Extra-Peninsular. In the one we find an old plateau system very little disturbed, which the labours of excellent geologists tell us has remained land for untold ages, while the adjoining area has received enormous volumes of sediment. The Tertiary alone, measuring 30,000 feet, has been upheaved and carved by denudation into the greatest mountain-system of the globe—the Himalayas.

These two countries might have been placed before us as a great and striking lesson in physical geology.

Britain.

If we turn to our own little isle, the chosen home of geological observation, the same lessons are impressed upon us, blurred and obscured no doubt, but still readable.

It is through the observations of the structure of far distant countries by observers who are now repaying the debts owing to the great fathers of English geology, that we are the better enabled to read the successive revolutions and movements of the earth which have produced the peculiarly involved geology of Great Britain and Ireland. It is the great glory of English geology that the stratigraphical succession of most of the formations has been worked out in this small area, and a classification adopted which has been generally followed throughout the known world. This has been achieved by patient labour in the field and great insight on the part of a succession of eminent geologists, beginning with William Smith.

But something more was wanted; the human mind will not rest content with knowing that the crust of the earth can be arranged and classified in order of time. It enquires into *causes*, and insists on knowing the why and the wherefore.

American geologists, by the enterprising nature of the surveys of their wonderful country, their elasticity of thought, their unwearying labours in the field, and by general ability, have contributed greatly to the solution of the intricate problems of mountain-structure.

A succession of European geologists, who have made the Alps their special study, have added much to our knowledge of the mechanics of mountain-building.

This information gained in fields afar has set us to work again in Britain, and perhaps for a time an analysis of the structure of mountain-systems will be best carried on in the great basal remnants of gigantic ranges which exist in the north of Scotland and in Ireland.

In the British Isles, as elsewhere, great movements of the earth, that is, movements producing bending, contortion, and permanent upheaval, have been ushered in by the previous laying down of immense bodies of sediment.

Thus, for the moment neglecting the Archean rocks, we find that the Cambro-Silurian period was one of great sedimentation; rock-masses of great thickness were deposited in Wales, the north of England, in Scotland, and in Ireland. During the Arenig time in North Wales there was a great outburst of volcanic activity, and several thousands of feet of lavas, tuffs, and volcanic agglomerates were ejected, and helped to build up the series.

This again occurred during the laying down of the Bala and Caradoc beds.

That the volcanoes were not the direct cause of the mountain upheaval is shown in the most striking manner by the volcanic beds being conformable to the sedimentary, and partaking of their folds and flexures.

The formation of the mountains of North Wales was subsequent to this particular display of volcanic activity.

In the Old Red Sandstone period, great volumes of sediment were again laid down, this time, according to Ramsay and Geikie, in inland seas and lakes *. Volcanic activity on a large scale accompanied the sedimentation. Along the line which now forms the Grampians, there were a series of volcanoes of the very grandest dimensions. Ben Nevis, and many others among the higher Scotch mountains, have been carved by denudation from the hard masses of granite, quartz,

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* Between the Ludlow group, "upwards in the geological series, we have to pass through some 10,000 feet or more of barren red sandstone" before we reach the marine fauna of the Carboniferous Limestone. Geikie, 'Text-book of Geology,' edit. 1, p. 693.

felsite, and other plutonic rocks which formed the central cores of these ancient volcanic piles. The remains of the great lava sheets and of the masses of volcanic agglomerate ejected from these grand Devonian volcanoes, make up hill-ranges of no mean altitude, like the Sidlaws, the Ochils, and the Pentlands *.

In parts of the bed of the Lower Old-Red-Sandstone sea were laid down rocks, "to a considerable extent the result of volcanic eruptions." †

In the district of Eastern Berwickshire, the Upper Old Red Sandstone lies unconformably upon the Lower ‡, but passes up by gradations into the Lower Carboniferous series.

With regard to the Devonian there has been much controversy, Jukes considering it to be the lower part of the Carboniferous series, other geologists the equivalent of the Old Red Sandstone, while some think it lies between the two. For our purpose we may consider the two periods practically as one. Sedimentation was continuous, though the conditions of the areas of deposition changed, and the volcanic activity was prolonged from the Old-Red-Sandstone era into the Carboniferous, but with diminished violence §. Under the joint reign of sedimentation and volcanism we may expect to find unconformability between strata of different ages in the same great series.

It was at the close of the sedimentation of the Carboniferous epoch, after enormous thicknesses of sandstones, limestones, grits, and coal-measures were laid down, that the second great upheaval of strata into mountain-ranges took place, when the Pennine chain and the Mendips were

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* 'Volcanoes,' Judd, pp. 274–5.

† "Geology of Eastern Berwickshire," Memoir of Geological Survey (A. A. Geikie), p. 21.

‡ Ibid. p. 34.

§ 'Volcanoes,' Judd, p. 275.

formed and the great Carboniferous tracts in the west of Ireland were upheaved. In Scotland an enormous tract of country lying between the Firths of Forth and Clyde—after the elevatory forces had expended themselves—was let down in a great trough fault. In what way faulting and dislocation are related to movements initiating the elevations and foldings, or to subsequent causes, will be discussed hereafter.

During the Permian and Triassic periods which succeeded the Carboniferous upheavals, sedimentation, commencing, according to Ramsay, in inland seas, finished in lakes possessing no outlets, the evaporation being so great as to allow of no overflow. In this way the salt beds of the Keuper Marls of Cheshire were formed. Whether we accept this explanation, first suggested by Mr. Godwin-Austen, or prefer Lyell's explanation, is not of great moment so far as the object of this enquiry is concerned.

That there were considerable thicknesses of sediment laid down is evident from the known depths of the Keuper and Bunter, in Cheshire and Lancashire. Volcanic action seems to have been dormant in the British Isles, though in European and American areas there were great manifestations of volcanism.

The Jurassic period followed without much apparent physical break in England. All over England, wherever the base of the Lower Lias is well seen, the Rhætic beds, rarely more than 50 or 100 feet thick, are found to lie between the Lias and the New Red Marl. As a general rule they are seen to pass conformably and by easy gradations into each other, and they were indeed always classed with the Lias till separated from these strata by Oppel*.

The Lower, Middle, and Upper Lias lie conformably upon each other in ascending succession. The Oolitic strata follow without any great physical break, the best proof of it being in the fact that the Midford Sands have been claimed by some geologists as belonging to the Lias, and by others to the Oolite*. Between the Jurassic and the Cretaceous a considerable break occurs, which, as pointed out by Judd, is specially noticeable in Scotland.

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* Ramsay's 'Physical Geology and Geography of Great Britain,' 5th edit. p. 159.

The Cretaceous, commencing with the Neocomian, succeeds the Oolite, and brings in a set of conditions quite different to any represented by the previous strata. With the close of the Cretaceous oceanic depositions, the calcareous sediments were raised into land, and continental conditions ensued, as is well shown by the enormous break that occurs between the life of the Cretaceous and that of the beginning of the Eocene. The line of unconformity between the two formations is most marked and striking.

With the beginning of the Tertiary, volcanic activity commenced to reassert itself in the British Isles, and attained its maximum in the Miocene. Eocene strata are confined to the south-east of England, the London Clay being the most important deposit. The Miocene, so far as is known, appears to be represented by a land surface in the British Isles; and it was during this period that those great outbursts of volcanic activity, so lucidly described by Prof. Judd†, occurred in the north of Ireland and west of Scotland, and the Hebrides, when enormous sheets of basalt were poured out, of which the Giant's Causeway and Fingal's Cave are but small remnants, and when volcanoes existed in Skye and Mull more than equal to Etna ‡.

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* "The Cephalopoda Bed and Oolite Sands of Dorset and part of Somerset." Buckman, Somersetshire Archæological and Natural History Society's Proceedings, 1874, vol. xx.

† "The Secondary Rocks of Scotland," Quart. Journ. Geol. Soc. 1878. "Volcanoes," "Address to Geological Section of British Association," 1885.

‡ "Towards the north coast the Miocene rocks attain a maximum depth of 5200 feet": Geikie, 'Text-book of Geology,' edit. 1, p. 764.

The Pliocene, the third and uppermost division of the Tertiary, is only represented by small patches of strata in Suffolk, called respectively the Coralline and Red Crag.

To trace out all this complicated course of geological history as dynamical cause and effect is very difficult, and we can do little more than guess at it.

Although the series of rocks from above the Lias are absent in the north-west of England and Wales, it does not follow that they were never laid down in those areas. The small patches of Lias on the borders of Shropshire and Cheshire, and other patches in the Vale of Eden, show, as pointed out by Prof. Judd, that the Lias most probably extended over the intermediate region*. The Oolite may have done so likewise, while it is almost certain that the chalk must have covered the whole area. As regards the Eocene there is not much evidence. Most probably this area has been subject to denudation since the close of the Cretaceous, excepting during periods such as the great submersion during the Glacial period. As I have before shown, in this area at present the rainfall is much in excess of that on the east coast; the land is also, even leaving the mountain districts out of account, at a greater elevation. Assuming that these conditions have prevailed since the beginning of the Tertiary period, there has been ample time, not only for the removal by denudation of the Cretaceous and Jurassic strata overlying the Trias, but for the removal in unprotected areas of the upper divisions of the Trias, and its total removal from portions of the adjoining Carboniferous tracts (see Plate VII. p. 37).

Prof. Judd's reasoning from the existence of isolated patches of Secondary strata in Ireland and Scotland and the surrounding areas, is to me conclusive in favour of the views I have just stated. I must refer those who wish for more information to the paper quoted.

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* A Problem for Cheshire Geologists; Proceedings of Chester Society of Natural Science, No. 3, pp. 45-9.

From the absence of these newer strata, where the development of the Trias is greatest, it is difficult to assign an age to the foldings and dislocations which have affected the Trias of the north-west of England. According to Ramsay, a great continental epoch began with the Old Red Sandstone, and closed with the New Red Marl.

From the general conformability existing between the Trias, Rhætic, and Lias, and between the latter and the Oolite, and the conformable succession of all the strata from the Triassic to the Nummulitic period in the area of maximum subsidence, *viz.* the Alps, where "the united thicknesses of all sediments accumulated along this great line of subsidence between the Permian and Nummulitic periods, probably exceeds 50,000 feet, or ten miles,"* we are rather led to infer that part of the dislocation of the Triassic strata took place in the Miocene period. Whether this be so or not, it is a remarkable fact, which struck me long before I began to consider this question, that the great Craven fault is one of the few cases in Great Britain where a fault influences the contour or orography of the ground. Here we have in Giggleswick Scar, on one side, mountain limestone of several hundred feet in height, forming what I would call a fault escarpment, worn back by denudation to so small an extent that the fault cuts the foot of the Scar, and in the valley we have millstone grit lying against the limestone (see view, Plate XII.). Tracing the fault northwards, we see it severing the Permian and Triassic rocks in the Vale of Eden, which are there faulted against the great scar limestone, and the fault along its whole length is the main feature in the scenery of the country. If we consider the way in which the faults, with which the Carboniferous strata are plentifully broken up, are,

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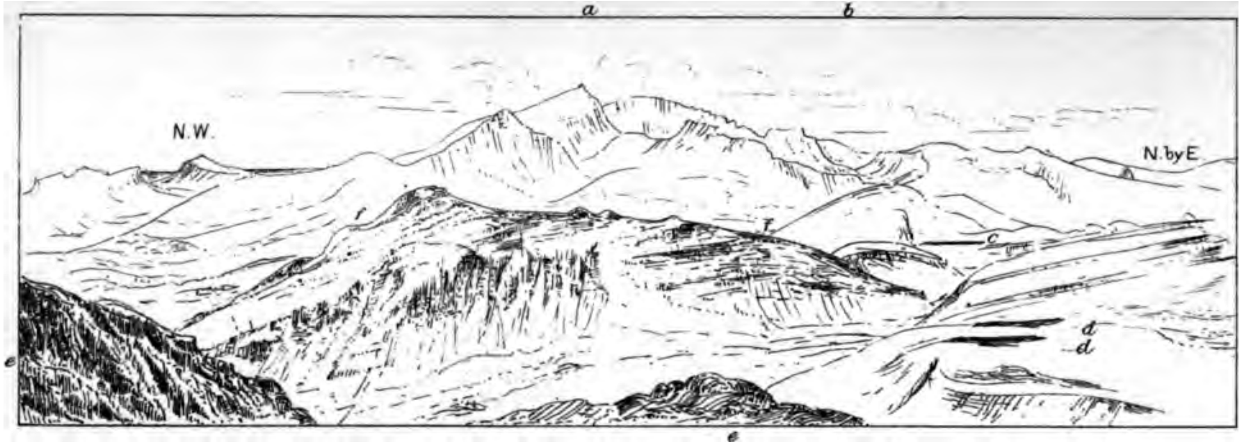
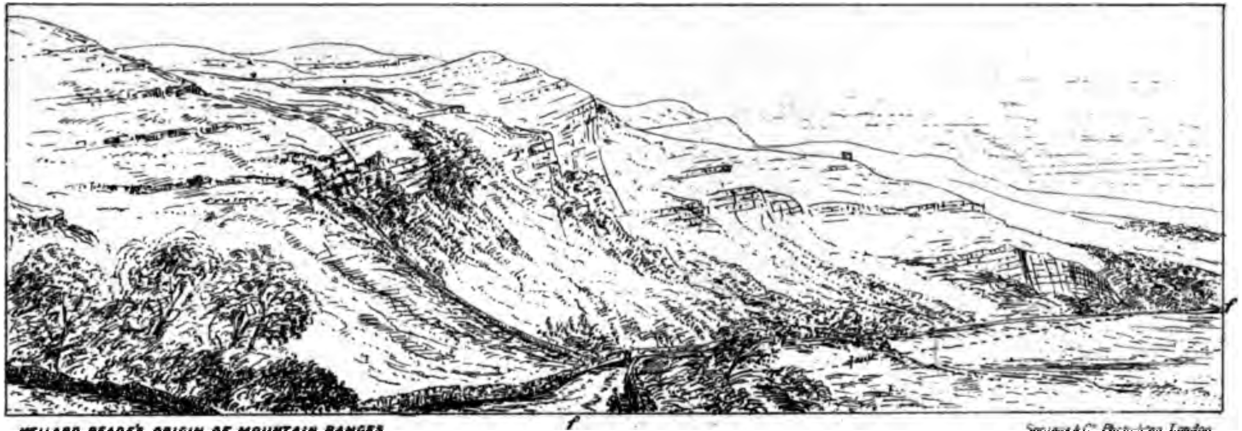
* 'Volcanoes,' Prof. Judd, p. 295.



SNOWDONIA from MOELWYN (Fig 2.)



MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

Sprague & C° Photo Litho. London

GIGGLESWICK SCAR (Fig. 1.)

PLATE XII.

Fig. 1. Giggleswick Scar, an escarpment of Mountain Limestone. The dotted line shows the line of the Great Craven Fault, to the right of which, on the downthrow side, the rock is Millstone Grit, the "Scar" on the left of the fault being entirely of Mountain Limestone.

It is a striking example—of which there are not many in Great Britain—of a fault greatly influencing the surface features of the country. As a rule, the two sides of a fault are planed down so as to obliterate the fault as a feature in the scenery (see p. 82).

Fig. 2. Snowdonia from the summit of Moelwyn. *a.* Peak of Snowdon. *b.* Pass of Llanberis. *c.* Llyn yr adar. *d*, *d.* Llyniau diffwy. *e*, *e.* Part of Moelwyn. *f*, *f.* Ridge of Cynicht.

The points of the compass are indicated at each side of the picture, in which the observer is looking towards the scarped faces of the ranges, the features of which can be understood on referring to the section of Snowdon given further on in this work.

although the throws are in many cases considerable, obliterated at the surface by the planing down of the inequalities of the strata on each side, it leads us to think that the Craven Fault is young compared with true Carboniferous dislocations* (see Plate XII., p. 81).

According to Dr. A. Geikie, a vast number of basalt-dykes range from the volcanic area of the Hebrides and Faroe Islands eastwards across Scotland and the North of England, and this system of dykes can be traced from the Orkney Islands southwards into Yorkshire and across Britain from sea to sea, over a total area of probably not less than 100,000 square miles †.

But although there was this enormous display of volcanic force, it is very instructive to find that mountain-building by folding took place on but a limited scale. At whatever period we place the upheaval of the Triassic rocks, this great fact remains, that the greatest upheavals and foldings took place where the sediments were thickest.

Professor Judd has shown that the Jurassic strata in the Highlands are from 3000 to 4000 feet thick, and are made up of alternations of marine and estuarine strata. At many different horizons beds of coal, and other indications of terrestrial conditions are found. The succeeding Neocomian Period was in Scotland an epoch of elevation and terrestrial conditions. That the strata suffered during this time enormous denudation is shown by the "relicts of the Cretaceous resting in turn upon every member of the Jurassic, the Rhætic, the Trias, and all the different Palæozoic and Archæan rocks." *

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* Prof. Hull in fig. 49, section near Alton, shows the Lower Keuper Sandstone broken into escarpments by a succession of faults. Memoir on the Triassic and Permian Rocks of the Midland Counties, p. 94.

The same thing occurs on the Peckforton Hills, Cheshire (ibid. p. 77), where a series of anticlinals and synclinals are, by successive faults, broken up into escarpments facing W.N.W.

† 'Text-book of Geology,' edition 1, p. 258. See also Prof. Judd's Presidential Address to the Geological Section of the British Association, 1885, Reprint, p. 17.

In England the Wealden, an estuarine or deltaic deposit of a great river probably flowing from this land, is the representative of this period.

What amount of undulatory curvature and faulting of the strata occurred during this period it is difficult to trace, but Prof. Judd is of opinion that the greater part of the faulting is post-Cretaceous, and in the Western Highlands displacements of several thousand feet not only affect the Upper Cretaceous, but also the upper Tertiary rocks.

In Scania, in Scandinavia, a plexus of faults have preserved rock-masses of Secondary age, and these faults have affected not only the Jurassic, but the youngest members of the Cretaceous †.

From these considerations we may well agree with Prof. Judd in believing "that it is impossible to avoid the conclusion that the whole of the North and North-western portions of the British archipelago—now sculptured by denudation into rugged mountain-land, were, like the South and South-eastern parts of the same islands, to a great extent, if not completely, covered by sedimentary deposits ranging in age from the Carboniferous to the Cretaceous inclusive; and that as a consequence we must refer the production of the striking and very characteristic features of those Highland districts to the last great epoch of the Earth's history—the Tertiary—and very largely indeed to the latest portion of that epoch, namely, the Pliocene." ‡

Switzerland.

But while the series of Geological events just described were taking place in the area of the British Isles, on the site of what is now Switzerland, rocks of the same ages, from the Permian to the Nummulitic period, were being laid down. The volcanic activity of the Permian, which preceded the deposit of this mass of rock, continued in a lesser degree through the Triassic period; and Triassic, Rhætic, Jurassic, Tithonian, Neocomian, Cretaceous, and Nummulitic strata were piled successively and almost uninterruptedly upon each other to a thickness, according to Prof. Judd, of probably 50,000 feet or 10 miles*. In the Oligocene period these enormous volumes of sediment became affected by earth-movements and lateral pressure, by which the strata were contorted, folded, and inverted in a most extraordinary manner, and permanently forced up into what are now the Alps. These movements not only affected the sediments described, but enormous masses of gneissic rocks upon which they were laid down were squeezed up to the surface, so that in some cases these lower rocks form the actual summits of high mountains.

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* Address to the Geol. Section, British Association, 1885, p. 14.

† Ibid. p. 16.

‡ "The Secondary Rocks of Scotland," Q. J. G. S. August 1878, p. 669.

This is well shown in the section across the Central Alps (Plate XIV. p. 98), here reproduced from Heim's monumental work.

Physical Inferences.

It seems a fair generalization from the foregoing geological information, culled from the most diverse sources as well as from personal observation, that no great range of mountains was ever ridged up excepting in areas of great previous sedimentation. Out of these sediments the mountains are mostly built and carved, but along with the newer and originally horizontal sedimentary beds, the older gneissic and Archæan rocks are usually thrust up, and often enclose in their folds strata of a newer age, which have become thereby considerably metamorphosed.

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* 'Volcanoes,' p. 295.

It is only in the great or in the old mountain-ranges that these old gneisses and schists are seen, because it is by denudation alone that they become exposed.

If these views of the relations existing between mountains and sedimentation be correct, and they are really only an extension and development of the expressed opinions of Hall, Dana, Le Conte, Judd, and most of the American geologists engaged on the United-States Survey, it is quite evident that mountain-building cannot take place without the following conditions being fulfilled:—

1st. The presence of large land-areas to supply the sediment by concurrent atmospheric waste. It would appear that the immense volumes of sediment required in mountain-building could only be provided by continental denudation.

2nd. An immense lapse of time for the sediment to accumulate; for though in imagination we may quicken the forces of nature, in reality such variations of energy have a very small range. The conditions of previous periods, as made known to us by Geology, do not warrant us in thinking that the forces of denudation differed much in energy in former time from those that now exist *.

3rd. It is often assumed that subsidence and sedimentation have exactly balanced each other. That is, sedimentation has proceeded at the same rate as subsidence.

In proof of this, the Coal-measures and also the vegetation of the Jurassic, Cretaceous, and Tertiary periods are pointed to, for terrestrial conditions are represented in one place or another in rocks of all these ages. There is, however, no occasion for the machinery of nature to be so nicely adjusted to the required ends. Such refinements usually belong more to mathematical theory than to the operations of nature.

In the Carboniferous formations in America, as in England, the basal beds are sea-deposits and largely limestones. The

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* It is only just to observe here, that a school of Geology, of which Prof. Prestwich is a distinguished representative, think differently.

terrestrial conditions come in as we ascend in the series. In the British Trias the Bunter Beds are considered to be inland sea-deposits, the terrestrial conditions represented by the foot-prints of the *Labyrinthodon* coming in with the overlying Keuper sandstones.

The same may be said of the Jurassic and Cretaceous. In America, India, and Europe, broadly speaking, the same succession occurs.

It is not necessary, in order to explain a succession of beds indicating terrestrial conditions, to invoke exactly one foot of subsidence for precisely one foot of sediment.

The land-surfaces may be the result of a levelling-up process if the land be stationary; or if the depression be slower than the sedimentation, by combined levelling-up and extension—or by depression, pauses, and levelling-up.

The conditions under which deposits are laid down are as various as are the land and drainage areas, the lakes, mediterranean seas, and ocean-basins. Sediment may accumulate in undisturbed areas and ocean-basins for enormous periods of time, as I have attempted to show it has done in the deposits of the Amazons and some other great rivers *. Or it may be laid down in areas subject to disturbance, as happens with the deposits of the Mississippi in the Gulf of Mexico; or in areas where it may mix with volcanic products, as in the Eastern Archipelago ; or in inland seas, as the deposits of the Volga in the Caspian, the Danube in the Black Sea, and the Nile in the Mediterranean ; or in shallow seas communicating with the ocean, as the Hoang-Ho or Yellow River delivers its burden into the Yellow Sea; or rivers may be engaged in filling up lake-basins, as the Rhone the Lake of Geneva.

All or any of these conditions may successively intervene in any area, and this is what we usually find has happened from the time of the Old Red Sandstone downwards. I am very much inclined to think that the comparative absence of representatives of terrestrial conditions in the Silurian areas of Great Britain may be due to denudation; or it may be explained by the areas in which such conditions occurred being inacessible to us. It is not to be supposed that Silurian land possessed no rivers, or that, possessing rivers, the rivers did not lay down deltaic or equivalent deposits. Yet where are they?

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* "The North Atlantic as a Geological Basin," Proceedings of Liverpool Geological Society, 1885–86.

We find all round our coasts, and we may almost say round every coast throughout the world, evidences both of recent subsidence and recent elevation within certain vertical limits —vertical areal movements apparently unaccompanied by any visible amount of contortion or dislocation. These movements, though limited, may affect vast tracts of land, so as to make them alternately areas of deposition and areas of denudation. This has clearly happened in the geological history of the Post-glacial beds of Britain, with which I happen to have an extensive acquaintance. The indentations of coast-lines also indicate in most cases subsidence.

By these vast areal movements, affecting sometimes thousands of square miles of land, alternations in deposition may be accounted for. At the same time, the balance of movement would appear to be—until mountain-making actually begins—downwards.

It is only necessary to appeal to most large rivers on the globe in proof of this *.

Thus it is seen that though the physical geography of an area of sedimentation may change enormously, it may still,

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* In "Rivers" (Trans. of Liverpool Geological Association, p. 14, reprint, 1882), it is stated—"One of the peculiarities of the great continental rivers, which I have never seen satisfactorily accounted for, is that the beds are usually far below the present surfaces of the deltas." "Oscillations of level have taken place no doubt, evidences of them are to be found everywhere, but why should the Ganges and the Mississippi apparently be both at the lowest swing of the pendulum."

considered as a whole, remain an area of sedimentation. It is in areas where the same conditions have existed for a great length of time, or successive changes have occurred altering the character and nature of the sediments, but without interference with the persistence of deposition, that mountain-ranges are built up*. Part of these areas may from time to time become land, as we find happened in the history of the Andes, the Rocky Mountains, the Alps, and the Himalayas, but depression and sedimentation on the whole has held sway.

Thus we arrive at our third conclusion, that varied conditions and areal changes of land and water are also the concomitants of mountain-building.

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* To Prof. James Hall is, I believe, due the credit of first clearly stating the relations of sedimentation to mountain-building. In a very suggestive Presidential address to the American Association for the Advancement of Science, delivered in 1857, but only published in 1882, he traced these relations in the geological history of the American continent.

CHAPTER VII.

EXCITING CAUSES INITIATING EARTH-MOVEMENTS AND MOUNTAIN-MAKING.

Leaving for the present the consideration of the causes producing vertical subsidences and elevations of the Earth's crust during the laying down of sediments, we will proceed to consider in what way the continuous additions of sedimentary upon sedimentary beds until their thickness is reckoned by miles—such as we see has always preceded mountain-building—will affect the physical condition of the Earth's crust. It is quite immaterial to this consideration, whether such beds have accumulated in what Dana calls "geosynclinals," or great bendings of the Earth, or have simply been built out from a continent in the form of submarine deltas, in the way I have attempted to show the Amazons is now laying down deposits in the Atlantic*.

In 1834, Babbage, reasoning upon the causes which have produced the oscillations of level of the Temple of Jupiter Serapis, in the Bay of Baiæ, pointed out that the addition of sediment to any part of the Earth's crust must raise the temperature of the portion of the crust it covers.

From this Babbage, assuming certain thicknesses of rocks, calculated the height they would rise by vertical expansion. Since this celebrated paper was written, containing the germs of much true reasoning on the Earth's crust, many geologists have attempted to apply the idea to account for Earth-movements. But strange to say with, so far as I know, the exception of one geologist, they have fixed their attention almost exclusively on linear vertical expansion. Consequently, as an explanation of mountain-building, the theory led to very little advancement. So far as I can gather, the first who appears to have seen clearly that expansion by accession of heat from below would affect the rocks horizontally as well as vertically, is Captain Hutton, of New Zealand. His paper "On the Formation of Mountains" * is well worthy of study. It happens that I had long worked at the problem from the point of view taken in this work, before my attention was directed to his theory. He added linear expansion as an effect of heating to the list of efficient causes of mountain-elevation, and calculated the anticlinal rise a given length of rock would produce with a given accession of heat. This principle he applied to account for the anticlinal of the Weald through the rise of the isogeotherm, caused by sedimentation, and to mountain-building generally †. The theory, which met with an opponent in the Rev. O. Fisher, seems to have taken little or no hold of the minds of geologists, principally, I believe, from its apparent quantitative inadequacy. It marked, however, I venture to think, a distinct advance in geological physics.

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* "The North Atlantic as a Geological Basin," Presidential Address to the Liverpool Geological Society, 1885–86.

Linear expansion is, however, only part of the effect that follows the heating of solid bodies like a portion of the Earth's crust. Superficial expansion—that is expansion in two directions—and expansion in volume, or in three directions, all of which geometrically follow from linear expansion, are, as I hope to show, far more powerful factors in mountain-building.

Nor need we be confined in our theory to the exact

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* 'Geological Magazine,' 1873.

† "On the Formation of Mountains," Geological Magazine, 1873, pp. 166–174, also 1874, pp. 22–28.

increase of temperature due to the raising of the isogeotherms in the Earth's crust by the deposits of sediment, as I also hope to make clear.

The deposit of such masses of strata as the Alps are built of is a process of nature, lasting many millions of years.

During the time of laying down, the compression of the lower beds, by the superincumbent weight, increases gradually until it becomes enormous. The weight of a column of rock weighing, say, 15 feet to the ton, will be 352 tons to the square foot for every mile of depth, or 3520 tons per square foot for 10 miles. The crushing weight of granite in cubes is about 720 tons per square foot on an average. The mean crushing strength of cast iron is about 5500 tons per square foot.*

It is quite evident from this that not only will originally plastic beds become condensed, but that rocks, such as consolidated granites, whinstones, and sandstones, will act under a pressure of 10 miles of overlying rocks as plastic materials.

From these considerations it is also evident that we may treat rocks at depths of 2 miles and over, whether originally of soft mud or clay, as perfectly solid matter. Solid by compression, but ready to flow one way or the other as the pressure may be reduced or increased. It is impossible under these conditions that cavities, unless filled with compressed gases or superheated steam, can exist in the rocks below a certain depth of superincumbent strata. It is necessary for the apprehension of any reasoning on earth-movements, whether they be lateral or vertical, that this fact should be distinctly realized.

From this it follows that contraction of beds due to drying or parting with the water originally contained in the interstices of their component grains or particles cannot produce fissures, because any such tendency will be counteracted by the longitudinal extension due to vertical pressure. We may easily realize from this that beds of the most diverse materials will become solidified by pressure so as to act together as one mass. A mass of rock ordinarily rigid may under conditions of time and pressure become plastic. This we see has happened in most geological deposits originally deeply buried, but which by uplift and denudation have become exposed to view.

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* See Kinnear Clark's Tables for Engineers, edit. 1, pp. 631 and 554.

Upon these manifestations of plasticity I propose to dwell at greater length, when I come to treat of the involved foldings which are found in mountainous regions.

Effect of Heat on the Consolidated Strata at Great Depths.

It has been shown by Dana, Le Conte, Judd, and others that the effect of the superposition of such vast masses of rock or sediment as are found in great mountain-chains, will be to raise the temperature of the lowest beds very considerably. So much so, that it is suspected the lower bend of the geosynclinal may sometimes become actually softened. This is simply a numerical application of Babbage's principle.

There is, however, no certain instance of the lower sedimentary bed having in this way become molten. I have shown that the fusing-point is not reached with an increment of temperature of 1° Fahr. for every 60 feet at a less depth than 33½ miles (p. 9).

Between the lower sedimentary beds of the series of deposits making up a mountain-range and the original isogeotherm of fusion, a series of pre-existing rocks or materials of the crust may, by the rising of the isogeothern of fusion, become molten. Molten matter, however, shows itself in mountain-masses as granite or analogous rock, that has been injected into the stratified beds, some of which may have been melted by contact *.

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* There seems to be considerable difference of opinion as to whether this takes place or not on a large scale.

For the purposes of mountain-building, below a certain depth we may consider all the rocks, excepting igneous injections, as practically solid but plastic, their plasticity perhaps being increased by heating. With a depth of 10 miles of sedimentary beds, all of which have been laid down at the surface at a temperature of say 50°, the bottom beds would be raised at an increase of 1° Fahr. for 60 feet, 880° Fahr., or to 930° Fahr.

At the same rate of increase there would still be some 20 miles of unmolten rock between the bottom beds and the isogeotherm of fusion. But the whole of that 20 miles of rock would have been raised in temperature 880° Fahr.

It is extremely probable that while an area is subsiding the isogeotherms are sinking also, and that the after-raising of temperature or rising of the isogeotherms is an extremely slow process.

The first effect of the rise of temperature on new deposits would probably be condensation of the lower beds by the lateral expansion of the mass. The underlying old rocks being more consolidated and rigid, would not yield to so great an extent in this way, but would adapt themselves to the volumetrical expansion by "flowing" upwards. The underlying *couch* of rock melted by the rising of the isogeotherm of fusion would also be under extreme tension, ready to flow as a liquid in any direction as the strata above gave way.

When I speak of molten rock I mean *potentially* molten, that is at the temperature of fusion at the surface of the Earth. We will, however, assume that at the normal depth we place rock of that temperature, namely 30 miles, it would be practically solid, but ready to flow with accession or relief of pressure.

Thus under such a sedimentary area, successive portions of the Earth's crust may be considered as in three different conditions.

1st. In the ascending order a *couch* or lateral mass of molten or plastic rock under extreme tension struggling to find vent.

2nd. A mass of rock 20 miles in thickness the bottom of which shades off into the plastic mass beneath, the top being *rigid* rock as we understand rigidity at the surface.

3rd. 10 miles in thickness of new deposits undergoing consolidation.

It is evident, if we accept these as the probable conditions of the crust in such a locus, we have a machinery of mountain-making that will cause compression, elevation, folding, and flowing and produce structural and orographic alterations on a stupendous and diverse scale. I hope also to show that forces would be developed, competent, combined with denudation, to account for the various forms and structures of the mountain-chains that have been already described.

Once the great series of deposits we have assumed are in the throes of mountain birth, it is evident that the molten matter, under the enormous compression produced by expansion, struggling to free itself will be injected upwards and laterally among the older and newer rocks, its course being determined solely by the lines of least resistance. In this way it will, at one place or another, reach the surface, and establish itself in a permanent volcanic form.

The injection of molten rock into the strata above will intensify the heating of the rocks first initiated by the rising of the isogeotherm. Hence further expansion, renewed lateral pressure, and more earth-throes. When volcanoes are permanently established, every overflow means an accession of heat. With every new manifestation of energy, there occur new rifts, so that in some cases we find the strata are cut up by a plexus of dykes.

The flow of the heated matter from the molten *couch* of rock will bring up such a continual accession of heat, that the strata it first flows against will in many cases be melted.

If a plate of lead be bent into a saucer-like form and molten lead poured into it, at the point where the lead is poured in the bottom of the saucer will gradually melt, while around it will remain solid. In this way I conceive molten rock acts upon the earth's crust.

Simple contact, we find by geological examples, has been insufficient to produce fusion.

It is now almost universally admitted that mountain-making is a very long process. We have seen that the Andes have been the seat of volcanic energy from the time they were first initiated.

In the building of mountain-ranges expansion after expansion goes on for ages, strata are folded up, bent back, rolled out and extended. Solid rock flows like metal under the enormous development of pressure, until even anticlinals of hard gneissic rock may be forced up in the fan-like form found in the Central Alps (see Plate XIV. fig. 3, p. 98).

We may therefore legitimately conclude that the shape mountain-building finally assumes largely depends upon the thickness, area, and form of the component deposits.

Sedimentation is not only a direct cause of a local rise of temperature in the Earth's crust, but it is also an exciting cause of volcanic activity, which brings up into the mass of expanding rock constant accessions of heat, causing repeated expansions, each of which adds to the growth of the mountain-range.

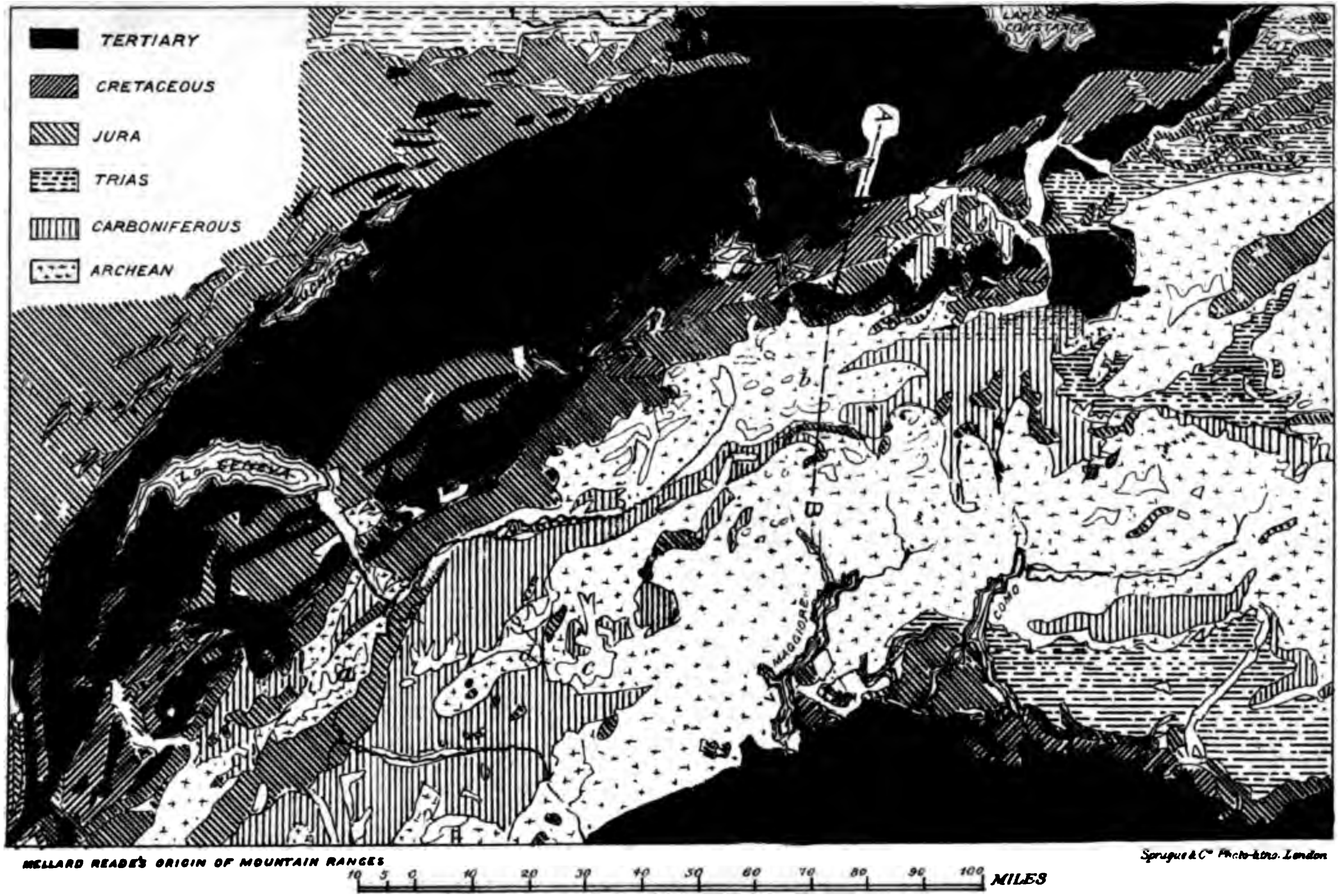
This is but an outline sketch, placed before the reader that he may be prepared for the special examples to follow.

Faults.—But mountain-chains, and even comparatively undisturbed strata, are traversed in many directions by dislocations called faults. What is the cause of these dislocations?

There are two classes of faults,—one consisting of fractures due to lateral pressure, as when closely packed strata that can yield no more by folding, shear along an inclined plane up which they are pushed. This is a form of fault mostly found in disturbed mountain-regions, and is known as a REVERSED FAULT.

The second, but by far the most frequent, is the NORMAL FAULT, which "hades" or inclines to the downthrow, and apparently results from a shearing of the rocks, by a subsidence of the strata on one side of the fault. This class of fault is universal in little disturbed strata (and is also found in stupendous examples) in mountain-districts. These two classes of faulting are frequently found in the same range of mountains. It seems impossible, from a variety of considerations, that the normal fault can arise from the same cause as the reversed fault, namely lateral pressure. It will be the object of the following chapter to inquire more fully into the nature and cause of normal faulting.

Plate XIII



MELLARD READE'S ORIGIN OF MOUNTAIN RANGES

Sprague & Co Photo-litho. London

PLATE XIII.

Geological Map of Switzerland, constructed from those of Studer, Escher von der Linth, and Heer. The shading is on the same principle as the preceding Maps. The line A B is the line of Section through the Central Alps, fig. 1, Plate XIV. It will be observed that the characteristic feature of a central gneissic area, or core, here of immense extent, obtains in the Alpine system as in that of the Rockies, and, as I have attempted to explain, in the Appalachians also. The highest Alpine peaks are of denuded Archæan rocks—as Mont Blanc, Monte Rosa, the Matterhorn, &c.

a. Mont Blanc.
b. St. Gothard.
c. Monte Rosa.
d. The Matterhorn.

In the Alpine system the gneissic area is not one continuous mass as in the Appalachians, on the contrary the crystalline rocks appear as distinct masses separated from each other by fossiliferous sedimentary rocks. Between Nice and the plains of Hungary Desor states that there are thirty-four such areas mostly showing a fan-like structure. When denudation has progressed to the extent it has done in the Appalachians these areas may become connected.

PLATE XIV.

Fig. 1. Section of the Central Alps on the line A B, Map Plate XIII., after A. Heim ('Mechanismus der Gebirgsbildung,' 1878).

A. Crystalline Schists, Gneiss, &c. (Archæan).	D. Jurassic.
	E. Cretaceous.
B. Trias.	F. Eocene.
C. Lias.	G. Miocene, Molasse.

The fan-structure of the St. Gothard massif, the type of many mountain cores, is well shown here, as also the loops of Jurassic rocks enclosed in the Archæan Crystalline Schists and Gneiss (see p. 95).

The folding of the Jurassie, Cretaceous, and Tertiary rocks on the flanks of the gneiss is most remarkable. There is no doubt that most of the formations have originally extended over the Archæan area, and that by the up-thrusting of the gneiss they have been burst asunder by tension, and thrown back on the flanks of the ranges.

For a detail of these structures Heim's work should be consulted, and also for mountain form and structure Mr. Collingwood's 'Limestone Alps of Savoy.'

Stapff's section on the line of the St.-Gothard tunnel may be seen in Prestwich's 'Geology,' p. 304.

Fig. 2. Section of the Mendip Hills (after the Geological Survey). Bearing of Section N. 5° 30′ E. from Milton Hill.

a. Old Red Sandstone.
b. Carboniferous Limestone.
b′. Argillaceous shales with bands of limestone in Carboniferous Limestone.
c. Dolomitic Conglomerate.
d. New Red Marl lying on Dolomitic Conglomerate.

A good example of anticlinals and synclinals planed down by erosion.

Fig. 3. Section of Snowdon (after the Geological Survey).

CAMBRIAN.

The Cambrian beds north of the great fault consist of "thick-bedded greenish-grey and purple quartzose sandstone and conglomerate.

LOWER SILURIAN.

a. Slaty and sandy beds.
b. Felspathic ashy beds.
c. Felspathic traps and conglomerate.
d. Greenstone dykes.
e. Dark blue and grey slates; bedding nearly obliterated by cleavage.

It will be observed that the trappean bedded rocks partake of the foldings, and that the faults (NORMAL FAULTS) are posterior to the foldings, (see p. 104).

f
Lower
5
1 Mile
&3
Hill
a
Finstera
Massif
D
15

CHAPTER VIII.

NORMAL FAULTING.—EFFECTS OF CONTRACTION ON THE PREVIOUSLY EXPANDED SEDIMENTS MAKING UP MOUNTAIN-RANGES.

THE subterranean energies, first excited by sedimentation, ending in the ridging-up of a mountain-range, though continuously alive for immense periods of time, act apparently by successive compressions and uplifts. Between these displays of force occur times of quiescence and local contraction. These minor contractions create local faulting, so that a range as a whole may be built up to a certain extent of dissevered parts. When the energies finally die out contraction occurs on a large scale, and thus those immense strike-faults, often running at the foot of mountain-ranges parallel to their axes, are produced.

In reasoning upon the cause of Normal Faulting, we must bear in mind that it is the lower beds of the deposits out of which the mountains are made, that expand most and are most folded and contorted. The upper, or surface-beds, suffer extension by the bending and bulging upwards of the strata, forced into this form by the rocks expansively struggling to adapt themselves to their new conditions of volume. It is from this cause that we find valleys of denudation situated more frequently on anticlinals than synclinals. By these extension or tensile fractures the denuding agencies—air and water, rain, streams, rivers, frost and ice—get ingress to play upon the upper strata of elevated rocks, and by combined chemical and mechanical means take them up in solution, or reduce them to powder to be again delivered into valley, lake, sea, or ocean, for the edition of a new chapter in the book of nature. But we rarely, we may almost say never, see these upper beds, because they are destroyed while the mountains are being built.

The contraction of the rocks will necessarily be greatest where the previous expansion had most distended them—that is, at the base. From the low tensile strength of rock, ranging from 21·6 tons per square foot in sandstone to 94·3 tons per square foot in whinstone *, it is impossible for rocks once expanded to reassume their previous form by contraction.

We have seen conclusively, from the experiments on sheets of lead, that that metal, even in small pieces measured by inches, cannot pull itself back to its original shape on cooling. How much less must this be the case with rock!

It is, however, possible, by the adhesion of the rocks to each other through the pressure of the superincumbent strata, that they may act together as *masses*. A contractile tension may thus affect them over a considerable distance and area. Whether the rocks in an area of contraction divide themselves into smaller or greater masses, each acting as a homogeneous whole, the result must be rifts or fissures—that is, rupture of the strata. These fissures, were they to remain open, would be greatest at the base, or nearest the zone of greatest contraction, at whatever level that zone might be situated. But I have attempted to show, from a consideration of the strength of rocks to resist compression—otherwise their crushing strengths—that no fissure could possibly remain open at the depths at which the greatest contraction takes place. The rock would flow to fill up the cavity.

But at the surface, and for a certain distance below it, the rock, having either no superincumbent pressure, or not enough to give plasticity, acting as a rigid body, would, with

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* Kinnear Clark's Tables, p. 629.

Plate XV

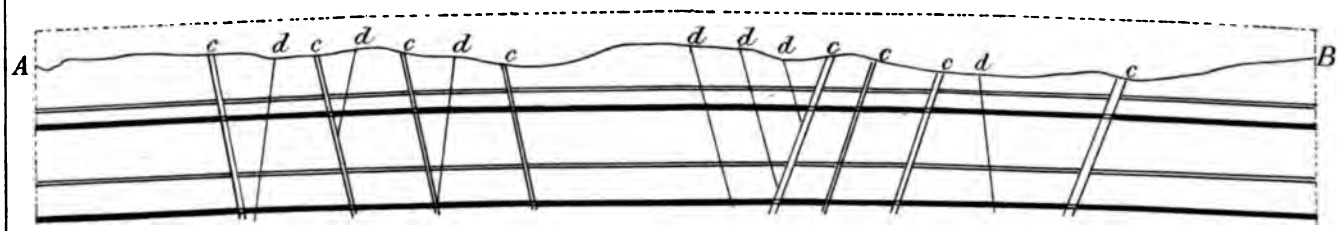


Fig 1

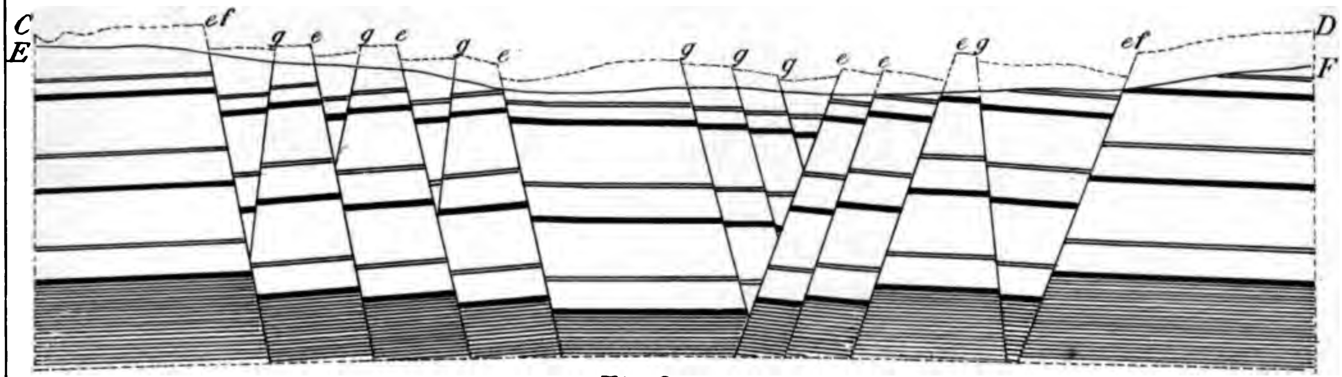


Fig 2

Furlongs 4 3 2 1 0 ¼ ½ ¾ 1 Mile

Horizontal & Vertical Scale.

MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

Sprague & Co. Photo-litho London

PLATE XV.

NORMAL FAULTING.

Diagrammatic Sections explanatory of Contraction or Normal Faulting.

Fig. 1. Section representing a series of continuous strata before being affected by throws due to faulting.

A B, surface unequally eroded by the atmosphere. The double lines, *c c c* &c., represent, in the positions where the main faults are initiated, an assumed horizontal contraction of the strata, due to decrease of temperature consequent on the depression of the isogeotherms. *d d d* &c., loci of subordinate faults.

Fig. 2. Section representing the faulting due to the horizontal contraction assumed in Fig. 1, combined with the consequent cubical contraction or decrease of volume of the strata represented, and also of the crust of the Earth below.

The rigid strata, which are represented to a greater depth than in Fig. 1, shear into wedge-like forms and key up by gravitation, as explained in the text. The dotted line, CD, shows the original surface, AB, Fig. 1, broken up by faulting. E F shows the surface planed down by further erosion; *e e e* &c. are the main faults forming part of one trough-fault from *e f* to *e f*. *g g g* are minor or slip faults sheared off the larger masses by subsidence or slips of the sides of the main masses towards the main faults.

The contraction is shown in Fig. 1 as equal along all the zones of rock. This is done for simplicity of explanation. In Nature the contraction is zero at the surface and increases with the depth, by which peculiarity the upper beds are in subsiding sometimes bent into slight synclinals; but these curved portions are often not to be seen, from having been destroyed by denudation.

The depth to which faults shear the crust of the Earth is unknown; but in the case of main faults it must be enormous, as a throw of 10,000 feet in a NORMAL FAULT is sometimes met with. NORMAL FAULTS are in some cases measured by thousands of feet, in others by inches.

It has been shown by J. Bauschinger (Min. of Proc. of Inst. of C.E. Foreign Abstracts, vol. lxxxiii. p. 448, 1886), in some experimental investigations into the laws of compressive strength, that the chief forms of the fragments produced by crushing stone of all kinds are, without exception, the wedge and the pyramid. With prisms of a height equal to the sides of a square circumscribing the base, two pyramids are formed having their bases in the surfaces under pressure.

the slightest inequality of settlement, at once shear, and initiate a fault from the surface downwards.

The contracting rocks, solid, but acting at great depths as a plastic mass under the extremely slow movements that take place, differ in their relative strengths to resist the superincumbent pressure. The result must be differential subsidence. But this subsidence can seldom be met by bending. Shearing strains accumulate until they become too great for the strength of the overlying rocks, which then suddenly snap, and the strata is cut as with a knife.*

The nearest parallel to this state of things is that of the walls of a building on a foundation of differing degrees of solidity. If the foundation be throughout altogether unyielding, the walls will stand firm and solid. Even if the ground be of a yielding nature, if it be equally yielding over all the area, and the areas of the "footings" be adjusted to the weights of the respective walls, it is possible to build so that rifts will not occur, because the whole structure will settle down equally. It is, however, very difficult to attain to this degree of perfection, as any one who has attempted it knows. With the best adjustments rifts or "settlements" will occur here and there. If, however, the building be placed on a foundation hard in one place and soft in another, it will very soon tear itself to pieces. Any one who looks at a "settlement" in a long brick wall will better appreciate what a fault means.

We are now in a position to understand why faults generally "hade" or incline to the downthrow. Any fault having an inclination from the vertical, be it ever so slight, must have on its downthrow side the rocks possessing the smallest base. On that base, by the overhang of the rock towards the fault, there is necessarily a greater pressure per square foot than on the base of the rocks occupying the other side of the fault, consequently the overhanging rock sinks and tilts towards the fault.

---

* The late John Phillips very acutely observes :—"There is, however, one important distinction between displacement by a fault and displacement by a flexure; faults, on the whole, leave the displaced beds in a space horizontally *wider* than the measure of the beds; but flexures have often the effect of packing so to speak a certain breadth of beds in a less width than they occupied before the movements." Memoirs of the Geol. Survey of Great Britain (The Malvern Hills), vol. ii. pt. i. p. 141.

The yielding strata beneath at the lowest depths flows to close up the fissure. It is evident that a fault once initiated in this way *must* by slow degrees increase in throw as the volume of the underlying rocks decreases by cooling. The faulting cannot in fact stop until either the contraction ceases, or some other earth-force comes into play. Like the rift in a building, this dislocation increases so long as the foundations continue to settle.

Faults usually have an inclination from the vertical. It is evident that if two faults incline towards each other, as they frequently do, the rock-mass between them as it subsides will close up the fissures or "key" itself in between the adjoining strata. At the surface of the earth, at a depth below climatic variations of temperature, no alteration of length takes place by expansion or contraction, as the strata remains always at the same temperature. Between the zone at which the solid rock will flow through pressure, and the surface which does not change dimensions, there remains an intermediate portion where the rocks by contraction, excepting for subsidence and tilting, would leave open fissures. Thus a decrease of temperature of a mass of rock of 100° Fahr. means a fissure of 2·75 ft. wide for every mile in length. By the sinking of the arch-like blocks, and the tilting of other blocks, most of the fissures close up or probably rarely develop, because of the continuity of the filling-up with the contraction.

In nature we find faults, except when opened out by surface denudation, usually tightly closed up, sometimes with "fault rock" between. So effectively sealed are they by these processes of nature that they are usually water-tight. Instance the fault in the middle of the river Mersey occurring in the Bunter sandstone, which was penetrated by the Mersey tunnel, but gave no trouble, though there is from 60 to 80 feet of water over the river-bed, according to the state of the tide. By the subsidence of the wedge-like masses of superincumbent strata in a faulted district, it is seen that, though the strata is actually shortened by contraction, the space is bridged over, and the crust remains solid. The solidity and continuity of the earth's crust is therefore maintained throughout all time by two processes—namely, at great depths by plastic movements or compressive extension, and above by a wedging of the rigid strata.

Before entering upon the next chapter, it will be well to consider the possibility of faults being created by up-thrust, as this is the more frequent explanation of faulting. Without denying its possibility, I think such cases are not frequent. It is not easy to conceive a force acting from below, excepting expansively, and this must produce more or less lateral extension. If, therefore, compression be going on at the same time as differential uplift, the strata will be "nipped" hard and fast. It may be that this differential uplifting does sometimes occur in mountain-regions by faulting, where the faults happen to be vertical, or nearly vertical. This question will be more fully discussed when treating of the Plateau Province of Colorado.

It is, however, only by an appeal to nature that such problems can be satisfactorily settled. What is the evidence in our own country?

If we examine Ramsay's section of the Snowdon range which is reproduced in Plate XIV. fig. 3, p. 98, a very cursory inspection will show that the faulting cuts anticlinal and synclinal alike, and is therefore posterior to the folding.

An appeal to most geological sections of folded districts, excepting in the case of reversed faults, will exhibit the same features, and show anticlinals and synclinals that have once been continuous, sheared across, and dislocated by faults. It may be said that much of the information shown in sections is inferential, and so it is; but an examination of a clear section in nature where folds and faults occur together will usually show similar relations *.

On the next page, Plate XVI., are given several sections after the Geological Survey of England and Wales, so that a comparison can be instituted between the diagrammatic illustration (NORMAL FAULTING, Plate XV., p. 101) and natural sections. I have selected Coal-Measure sections in preference to any others, as the relations between the faults and the beds have generally been more accurately ascertained, and also because the well-marked zones and parallelism of the beds and seams afford clear illustrations.

---

* Mr. W. J. McGee has mathematically investigated some of these points in a paper, "On the Origin and Hade of Normal Faults," American Journal of Science, vol. xxvi. pp. 294–298 (1883). This paper is well worth study; the investigator proceeds on the assumption that normal faults are due to movements relieving radial strain. It will be seen that, by the introduction of the element of contraction, as in my explanation, the vertical or radial strains are accounted for.

PLATE XVI.

Selected sections, after the Geological Survey, exhibiting the characteristic features of NORMAL FAULTING.

Fig. 1. Part of section from the northern side of the Skipton anticlinal to the middle of the Yorkshire Coal-field (Horizontal sections, sheet 96). The whole length from *d* to *e* consists of Lower Coal-Measures resting on Millstone Grit.

a. Sandstones and flags.
b. Hard-bed coal and soft-bed coal.
c. Better-bed coal.

Fig. 2. Ditto. The section from *f* to *g* consists of Lower Coal-Measures resting on Millstone Grit; from *g* to *h*, Middle Coal-Measures resting on Lower Coal-Measures.

b. Hard-bed coal and soft-bed coal.
i. Six yards rock.
c. Better-bed coal.
j. Middle Coal-Measures.
j'. Thornhill rock.

Fig. 3. Part of section across the Somersetshire coal-field. (Horizontal sections, sheet 104, by J. Austen and J. McMurtrie, under the direction of Joseph Prestwich, F.R.S.)

k. Pennant grit.
l. Farrington seams.
m. Bed of red shale.
n. Great seam, Middle seam, Little seam, Bull seam, &c.
o. Dolomitic conglomerate.
p. Keuper Marl.
q. Penarth beds and Lower Lias.

The faults are not lettered, as the sections explain themselves.

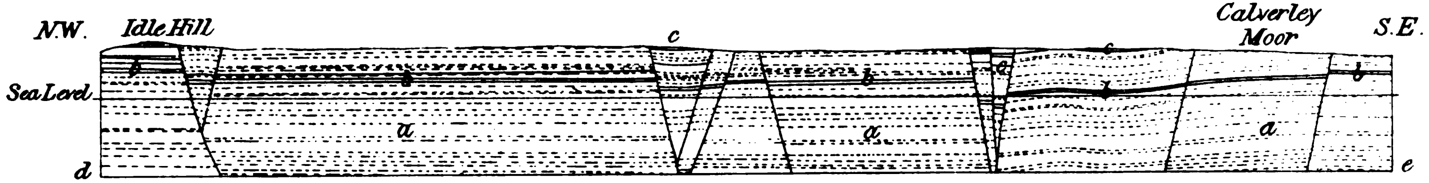


Fig. I

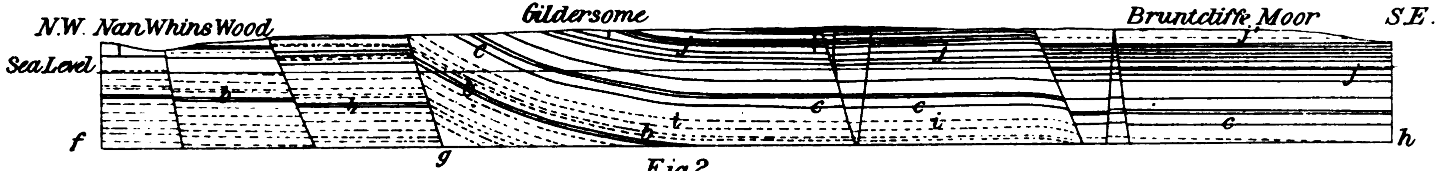
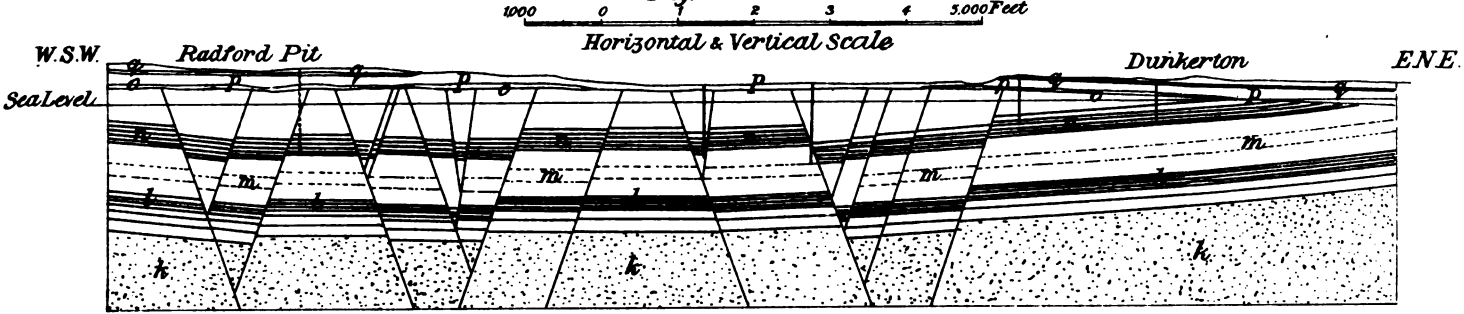


Fig. 2



MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

Fig 3.

Sprague & Co. Photo-litho London

CHAPTER IX.

COMPETENCY OF EXPANSION BY HEAT TO PRODUCE ALL THE PHENOMENA OF MOUNTAIN-STRUCTURE.

NOTWITHSTANDING the arguments already adduced, it may perhaps be said that expansion and contraction of the strata of the Earth by variations of temperature, while capable of effecting small changes of form in the crust, are insufficient to account for the building-up of mountain-ranges.

Let us therefore look into the question *quantitatively*, for few scientific problems can be settled without an accurate conception of the relative proportions of the materials and forces involved.

Coefficients of Expansion of Rocks.—There have not hitherto been many experiments made on the dilatation of rocks by heat, nor do those that have been published seem in all cases trustworthy, because the results differ so considerably *.

The difficulties in carrying out such experiments are much greater with stone than with metals. The expansion of metals can be tested with much longer bars, and the experiments can be carried on under conditions ensuring greater accuracy. As I always think it best, if possible, to make one's self practically acquainted with the behaviour of materials under conditions as nearly as possible those we assume in reasoning upon them, I instituted a series of experiments to determine the coefficients of expansion of various rocks.

---

* This may be seen on reference to the table given in Kinnear Clark's Manual, p. 337.

The experiments were in most cases made with dressed bars of stone about 15 inches long, but of various scantlings best suited to the material. The ends were dressed square. The measurements were taken with a pair of callipers of American make *, which measure accurately to the $\frac{1}{1000}$ of an inch. The bars were marked with a line, and the callipers applied in such a way that they always gripped the same spots. This was proved by frequent measurement at different times when the stone was cold. The temperature and measurement were taken and recorded before heating; and the bar to be experimented upon was placed in an ordinary oven, sometimes in a sand-bath with a thermometer inserted in the sand, and sometimes without the sand-bath, but always on a board. It did not seem to affect the result whether a sand-bath was used or not. The bar, when heated through, was taken out of the oven, the thermometer-reading carefully noted, and the bar measured again with the callipers, precautions being taken to prevent as much as possible the heat affecting the bar. A correction was made for this, and for the cooling of the stone during the time occupied in taking it out of the oven, and in the measuring. The experiment was in each case repeated several times and the mean of the observations taken as the correct result.

This method does not pretend to very great exactitude, but the results are, I believe, practically reliable. They do not in most cases greatly differ from those of Mr. Adie recorded in the Trans. Royal Soc. Edin. vol. xiii. p. 366, my mean coefficient being in remarkable agreement with his (see p. 111). On the following pages details of my results, together with those of Adie and Totten, are given:—

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* The "Improved Vernier Calliper," manufactured by Darling, Brown, and Sharpe, Providence, R. I.

TABLE of Coefficients of Expansion of various Rocks, as determined by the Author's Experiments.

	SANDSTONES.	Mean expansion per 1° Fahr.
No. 1.	St Helens	$\frac{1}{180{,}712}$
No. 2.	Hare Hill	$\frac{1}{202{,}870}$
No. 3.	Burnley	$\frac{1}{187{,}889}$
No. 4.	Fine sandstone (locality not given)	$\frac{1}{184{,}549}$
No. 5.	Runcorn (Red Triassic; Keuper)	$\frac{1}{183{,}984}$
No. 6.	Everton (Red Triassic; Bunter)	$\frac{1}{185{,}515}$
No. 7.	Micaceous Sandstone	$\frac{1}{166{,}556}$
No. 8.	Sandstone of a coarser grain than No. 7	$\frac{1}{189{,}062}$
	MARBLES.	
No. 9.	White Sicilian	$\frac{1}{196{,}724}$
No. 10.	Caen Stone	$\frac{1}{230{,}669}$
No. 11.	Irish Black	$\frac{1}{188{,}370}$
No. 12.	White	$\frac{1}{169{,}298}$
	SLATES.	
No. 13.	Burlington (Blue Westmoreland)	$\frac{1}{171{,}162}$
No. 14.	Llangollen	$\frac{1}{241{,}473}$
No. 15.	Penrhyn	$\frac{1}{171{,}465}$
No. 16.	Velenheli	$\frac{1}{164{,}755}$
No. 17.	Penmachno	$\frac{1}{216{,}730}$
No. 18.	Darbishire's Nantle	$\frac{1}{159{,}591}$
No. 19.	„ „	$\frac{1}{157{,}450}$
No. 20.	Penmachno	$\frac{1}{215{,}510}$
No. 21.	„	$\frac{1}{246{,}813}$

Table of Coefficients of Expansion (*continued*).

GRANITES.	Mean expansion per 1° Fahr.
No. 22. Rubislaw (Grey)	$\frac{1}{200,040}$
No. 23. Carngall (Grey)	$\frac{1}{251,696}$
No. 24. Hill of Fair (Red)	$\frac{1}{189,315}$
No. 25. Corrennie (Red)	$\frac{1}{172,240}$

Mean Coefficients of Expansion of various Classes of Rocks, per 1° Fahr.

Sandstones	$\frac{1}{178,825}$
Marbles	$\frac{1}{184,797}$
Slates	$\frac{1}{193,897}$
Granites	$\frac{1}{208,329}$

Mean of the whole $\frac{1}{190,192}$=2·77 feet per mile for every 100° Fahr.

Coefficients of the Expansion of Stone, as determined by the experiments of Mr. A. J. Adie (Trans. Royal Soc. Edin. vol. xiii. p. 366).

	Decimal of Length for 1° F.	
Sicilian White Marble	·00000780 = $\frac{1}{128,205}$	When moist.
" " "	·00000613 = $\frac{1}{163,132}$	" dry.
Carrara Marble	·00000662 = $\frac{1}{151,057}$	" moist.
" "	·00000363 = $\frac{1}{275,482}$	" dry.
Sandstone from the liver rock of Craigleith Quarry	·00000652 = $\frac{1}{153,374}$	" "
Cast iron from rod, 2″×2″	·00000637 = $\frac{1}{156,985}$	" "
" " ½″×½″	·00000612 = $\frac{1}{163,398}$	" "
Slate from Penrhyn Quarry, N. W.	·00000576 = $\frac{1}{173,611}$	" "
Peterhead Red Granite	·00000532 = $\frac{1}{187,969}$	" moist.
" " "	·00000498 = $\frac{1}{200,803}$	" dry.

Coefficients of the Expansion of Stone (*continued*).

	Decimal of Length for 1° F.	
Arbroath pavement	·00000499 = $\frac{1}{200,400}$	When dry.
Caithness „	·00000497 = $\frac{1}{201,207}$	„ „
Greenstone from Ratho	·00000449 = $\frac{1}{222,717}$	„ „
Aberdeen Grey Granite	·00000438 = $\frac{1}{228,310}$	„ „
Black Marble from Galway	·00000247 = $\frac{1}{404,858}$	„ „

The mean coefficient of the thirteen determinations of the expansion of stone is $\frac{1}{207,069}$; but if we omit the last coefficient, viz. that of the Black Marble from Galway (which is probably an error, being so much less than those of the other marbles and also of my own determination of the expansion of Irish Black Marble), the mean coefficient will be $\frac{1}{190,522}$, showing a remarkable agreement with my own results.

In Mr. Adie's experiments he used longer bars of stone, namely 23 inches long and from ½ inch to 1 inch square, and heated them with a steam-jacket, using a much more complicated apparatus than mine.

Coefficients of Expansion of Building Stone, as determined by experiments conducted by W. H. C. Bartlett by order of Col. Totten, 1832 (Amer. Journ. of Science, 1st series, vol. xxii. p. 136).

Granite . . .	·000004825 = $\frac{1}{207,253}$
Marble . . .	·000005668 = $\frac{1}{176,429}$
Sandstone . .	·000009532 = $\frac{1}{104,909}$
Mean . .	$\frac{1}{162,863}$

These experiments were made with three bars of the several stones mentioned, measuring 94 inches long (nearly). The measuring-instrument was a pine rod with copper elbows, fitted with a graduated wedge for measuring. The variations of temperature, ranging through 100°, were those due to the atmosphere, which affected both the measuring-rod and the stone, the actual expansion being calculated from the differences of expansion.

The object of these experiments was to ascertain the cause of the fissuring of the joints of coping-stones used in the works at Fort Adams, Newport Harbour, it being found impossible to keep the joints perfect for more than a few weeks, the conclusion arrived at being that the fractures were due to ordinary changes of temperature.

Cubical Expansion and its Effect on the Earth's Crust.—From the table appended it will be seen that an expansion of $\frac{1}{190,192}$ per 1° Fahr. is a fair coefficient for the rocks, considered as a group composing the Earth's crust. This equals 2·77 feet per mile for every 100° Fahr., say 2·75, as being easier to compute and to remember. This mean may be considered practically correct within the limits of temperature to which the bars were subjected, namely between 60° and 220°. We shall have in our reasoning to assume that the same rate of expansion continues to the higher limits of temperature affecting the Earth's crust, and that this is not in excess of the truth I have little doubt.

As I have before pointed out, Lyell *, Babbage, and others, with the single exception of Capt. Hutton, reasoning upon elevation and depression caused by expansion or contraction, confined their attention to linear *vertical* expansion. Capt. Hutton introduced linear *horizontal* expansion as the main factor in mountain-building. No one, so far as I can discover, seems to have perceived in connection with the Earth's crust, that increase of *volume* is the final result of expansion. Yet this must be the most potent of all in its geological effects.*

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* Lyell, using Col. Totten's coefficient of expansion for red sandstone (·000009532), calculated that a mass of sandstone a mile in thickness raised 200° Fahr. would lift a superimposed layer of rock to the height of 10 feet above its former level. Or a portion of the earth's crust 50 miles in thickness, equally expansible, raised in temperature 600° to 800°, might produce an elevation of between 1000 to 15,000 ft. By such an agency we might, he says, explain the gradual rise of part of Scandinavia, or the subsidence of Greenland. 'Principles of Geology,' 10th ed. vol. ii. pp. 235–6.

This is *linear* expansion only; *cubical* expansion, which has not been thought of in this connection, would raise it three times the calculated height.

Let us pause to consider what will happen if a cubic mile of solid rock be heated 100° Fahr. If free to expand in all directions, it will increase in dimensions to a cube measuring 1 mile 2·75 ft. at the sides. Prevent this cube by some means from expanding in more directions than one, say leave it free to expand upwards, and then consider what will occur. It will then, unless the surplus volume be disposed of by condensation of the rock, measure 1 mile × 1 mile at the base and 1 mile and 8·25 feet high (nearly), or the surface will be raised vertically three times as much as what would be due to linear expansion alone. This is why the expansion of water in a vessel is so apparent. It can only dispose of the increase of volume by rising vertically. (See Illustrations, Plate XVII., p. 117).

Let us now apply this principle to a portion of the crust of the Earth heated 100° above its normal. In the way I have assumed the local heating takes place, the superheated rocks would form a lenticular patch in the Earth's crust. It is evident on very little consideration that as the expansion cannot take place laterally or downwards, the rocks must act as in the preceding example. That is, if the rocks were uniformly and proportionately acted upon, the rise at the surface would be three times the linear expansion, so that a crust 20 miles thick, heated 1000° Fahr., would rise 1650 feet, instead of 550 feet, the result calculated in Lyell's way. This is an enormous difference, strangely lost sight of.

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* Since this was written, Mr. G. K. Gilbert, in a note appended to his Presidential Address to the American Society of Naturalists, Dec. 27, 1885, p. 298, says that a friend had pointed out to him that "horizontal expansions would almost necessarily be converted into vertical uplifts." This is interesting as being the first recognition of the fact that I have seen in print.

But this is seldom, if ever, the way that rigid rocks would be affected by the expansion of volume that takes place in heating. On the contrary, they would more frequently begin to rise in a linear ridge determined by a line of weakness. They would adapt themselves to the lateral expansion and increase of volume by anticlinal and synclinal folding, forming a ridge, or series of ridges, elevated to a far greater height above the surrounding country. A considerable portion of the increase of volume would, as may be seen from the experiments already detailed, be disposed of in this way. It is evident that, if all the surplus matter were thrown into a ridge having a base one tenth of the total area heated, the resultant heap must be ten times as high, or 16,500 feet, or, if pyramidal in section, double that height. The *couch* of molten or half-molten rock below the rigid crust would expand in a lenticular manner, perhaps intruding itself horizontally among the surrounding strata along lines of weakness, but in its behaviour governed largely by the character and structure of the bounding rocks. This I venture to think is borne out by the physical structure of mountain-systems, in which, as in the Rocky Mountains, there is usually a gradual rise over an extensive country, until the base of the ranges is reached *, when the steep grades, folded and contorted rocks, and vertical precipices, distinguishing mountain-structure, occur.

But a mountain-range is not the result of *one* display of energy. It is seen in the Andes, and still more clearly in the Rocky Mountains, that though a mountain-range be the seat of volcanic energy for untold ages, such energy manifests itself by successive but long continued outbursts at different periods. According to my view, an outburst means an increase, a dormant period a decrease, of subterranean heat. Every alternation will have its effect, the total of each alternation ending in an additional uplift. That these uplifts are continually taking place throughout the geological history of a mountain-range, we have the strongest evidence in the Rocky Mountains and the Andes. The attentive study of the work of American geologists leaves no doubt of it in the former case, and Mr. Darwin's observations prove it, though not perhaps so conclusively, in the latter.

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* As Mr. Ruskin tellingly puts it, "The great mountains *lift* the lowlands *on their sides*." 'In Montibus Sanctis,' Part II., p. 48.

We thus see that both contraction and expansion must be going on during the building of a mountain-system, and the subterranean strata of one portion of a long range may be expanding while another is contracting. A mountain-system is an area of continuous movement, the crust is never at rest.

Effective Increase in Cubic Miles of a given Heated Area.[*]

Let us now consider what would be the quantitative effect towards the ridging up of a mountain-range of a rise of temperature in a given area and depth of rock. Take a volume, for example, equal to 500 × 500 × 20 miles, that is 5,000,000 cubic miles. If this were heated to a mean of 1000° Fahr.[†], a temperature that must have occurred over and over again in the local heating of the Earth's crust, there would be a linear expansion in two directions of 500 × 2·75 ft × 10 = 13,750 feet or 2·6 miles. Now if we compare this area with many of the areas of deposit out of which mountain-ranges have been built, it is very small. It is little compared to the deposits constituting the Andes or the Rockies, and still less to those of the Himalayas; or, to go further back into the Earth's history, either the Appalachian sediments or those out of which the Silurian mountains of Britain have been carved. Yet even in the example assumed, the increase of volume would be 52,135 cubic miles, or over one fourth the bulk of the Old Red Sandstone of Britain as calculated by Dr. A. Geikie *.

---

[*] It is perhaps necessary to explain that by *effective* increase of bulk is meant expansion horizontally in two dimensions. Vertical expansion raises the whole body of rock but does not contribute to horizontal displacement and consequent permanent ridging-up.

[†] A series of alternations of temperature amounting in all to 1000° F. will give nearly the same effective increase of bulk. This will be explained more fully further on.

It is impossible to reason correctly upon the physical phenomena of the Earth without we constantly keep in mind the real living proportion of things. Though the results seem so large, the block of crust (5 millions of cubic miles) we have been operating upon is only the $\frac{1}{51,875}$ part of the solid matter of the whole globe.

This fact brings clearly to the mind the truth, often pointed out, but seldom realized, that the greatest of mountain-ranges are but trifling excrescences on the surface of the globe †.

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* Phillip's 'Geology,' by Etheridge, 180,000 cubic miles.

† The Earth contains 259,373 million of cubic miles according to Herschel, 'Outlines of Astronomy,' 9th edition, p. 560.

Plate XVII.

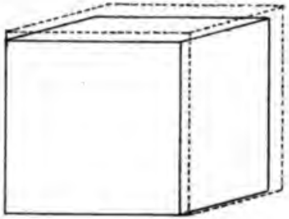


Fig. 1.

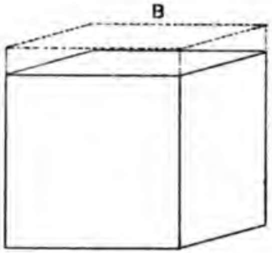


Fig. 2.

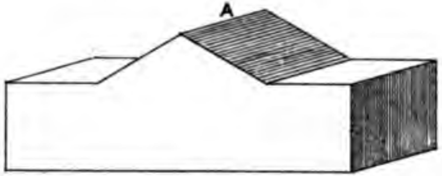
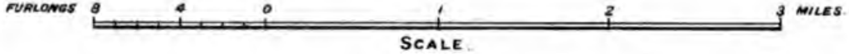


Fig. 3.



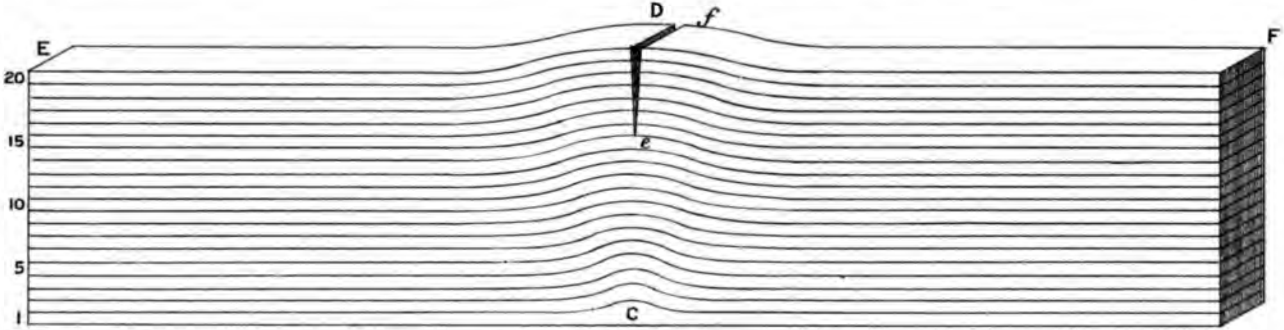


Fig. 4.

MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

Sprague & Co Photo-litho. London

PLATE XVII.

Diagrammatic Illustrations of several Effects of Cubical Expansion.

Fig. 1. Represents a cubic mile of rock expanded lineally $\frac{1}{20}$. The firm lines give the normal cubic mile, the dotted lines the expanded cubic mile. In this figure the block is assumed to be in a position to expand freely in all directions.

Fig. 2. Represents the same total amount of cubical expansion, the block being assumed to be so bounded as to be unable to expand otherwise than vertically. The vertical rise is three times that of fig. 1 (nearly).

Fig. 3. Represents a rectangular block measuring 2 miles by 1 mile by ½ mile=1 cubic mile. The block is assumed to be expanded to the same extent as figs. 1 and 2, but the surplus material distributed as a ridge, A, which is equal to the block B shown in dotted lines. The effect is similar to what would happen if the block were expanded in a mould of this exact form and size, the mould itself remaining unexpanded.

Fig. 4. This represents a series of beds of rock (20 in all) expanded by being raised to the same temperature throughout. This block is assumed to be bounded so as to be unable to extend itself horizontally. The thickening of bed No. 1, due to horizontal expansion, is concentrated at the anticlinal C. Each plate in succession individually expands to the same extent as No. 1. The cumulative result being the anticlinal D. The fissure *e f* represents the rupture caused by the expanding arches below, all the beds above No. 13 having been subject to tension.

The whole block has expanded vertically to the extent of its normal linear expansion; the horizontal expansion has expended itself in raising the anticlinal C, D.

This shows to a true scale the effects of the heating of a portion of the Earth's crust=to 1000° Fahr. increase of temperature. The vertical rise of the top plane E F, is $\frac{1}{192}$ of the thickness of the block, and the remaining cubical expansion thrown into the anticlinal by horizontal pressure is $\frac{1}{96}$ of the cube of the whole block.

NOTE.—Since the above was written and the diagram drawn, I have proved experimentally, by the lateral compression of a series of layers of clay with calico partings, that the reasoning is correct.

CHAPTER X.

THE GLOBE AS A RESERVOIR OF HEAT.

The question will probably be asked, Can the Earth's crust go on receiving heat from below, expanding and parting with it on the scale pictured in the previous chapter, without its store of heat becoming rapidly exhausted?

This problem is intimately related to the total amount of foldings and uplifts which have taken place in the Earth's history, and it also involves considerations of geological time.

Unfortunately it is impossible from present knowledge to calculate with much accuracy the gross total of mountain uplifts which have occurred during geological history.

Suppose for the sake of enquiry we divide the time which has elapsed from the beginning of the Cambrian to the present time into 10 periods, and to each of these periods allot 10 uplifts, equal to that upon which our last calculation was founded, namely (500 × 500 × 20) miles × 10. This would be equal to a portion of the Earth's surface 5000 miles long by 500 miles broad and 20 miles deep. If this amount of rock were heated 1000° Fahr., we should have a volume of 521,350 cubic miles for each period for mountain-building, or a mass equal to a single mountain-range of triangular section 21 miles at the base, 2 miles high, and the length of the mean circumference of the globe taken at 24,900 miles. Ten such periods as these would give us

5,213,500 cubic miles for the whole period for mountain-building, or 10 such chains as I suppose.

This would require the heating to 1000° Fahr. of 500 million cubic miles of rock. Now as the whole globe contains about 259,373 million cubic statute miles, if the mean temperature of the globe is only 6000° Fahr., a very low estimate, the raising of all this mass of 5,213,500 cubic miles into mountain-ranges from the Cambrian times until now (inclusive) would only exhaust about the $\frac{1}{3112}$ part of the total heat of the globe.

Again, if we carefully consider the problem, we shall find that this is not heat wasted in addition to that constantly escaping through the secular refrigeration of the globe. Rather it is part of this heat, which would otherwise be wasted, used up in the production of the mechanical work of mountain-building.

Nor must we lose sight of the probability of the existence of a conservative force, consisting in the chemical reactions that probably take place among the materials of the crust, when subjected to these extraordinary changes.

These calculations are merely given as an illustration, certainly not with any view to accuracy; the proportions may be varied at the discretion of the reasoner, but I think the impression left on the mind from the process will be that the internal heat of the globe is abundant enough to account for mountain-building by local expansion.

Especially will this be the case when we consider that the loss of heat by the cooling of a crust or shell 30 miles thick over the whole globe, from 3000° to a mean of 1500° Fahr., would involve a vastly greater loss of heat than that required for the mountain upheaval in these calculations, in fact over 17 times as much *.

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* This is considering the shell alone, exclusive of the secular refrigeration of the sphere below.

It is quite evident, if our globe has been orginally molten, that a much greater loss of heat has occurred in the cooling of the crust alone than is required for the mountain uplifts in our example.

But we are not confined to a mean temperature of the globe of 6000° Fahr.; it may be more now and in early periods may have been greater still, if the secular refrigeration hypothesis be correct*.

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* The temperature of solidification is taken by Sir William Thomson at 7000° Fahr.

CHAPTER XI.

EXAMINATION OF THE HYPOTHESIS THAT MOUNTAIN-RANGES ARE RIDGES THROWN UP BY THE COMPRESSION INDUCED IN THE RIGID CRUST OF THE GLOBE BY A SHRINKAGE OF THE HEATED NUCLEUS.

I HAVE already attempted to show, principally by geological considerations, that the compression of a rigid crust through tangential strains set up in it during its gravitation towards a contracting nucleus, does not satisfactorily account for many of the phenomena associated with mountain-building.

So far I have, for the sake of investigation, left unquestioned the possibility of a sufficient development of compression and tangential strain arising in this way to account for the upheaval of mountain-ranges.

Perhaps it may be considered a hazardous thing to controvert this opinion, adopted, as it has been, by so many eminent men, but it seems so clear to me that such a result does not necessarily follow from the hypothesis, that I venture here to state the reasons which have driven me to this conclusion.

First, then, I may point out that an important link in the chain of reasoning has been omitted, inasmuch as the shrinkage of the solid shell itself through the gradual cooling of its lower zones has been unconsidered in the application of the hypothesis.

In the cooling of a sphere from the exterior, the first strain set up would more likely be one of tension than of compression, from the contraction of the external shell. But we may waive this point as not material to the issue, and accept the existence now of a solid shell, say, for the sake of easy calculation, 30 miles in thickness, the outer surface being at a temperature of 50° Fahr. and the inner 3050° Fahr., such a shell being the nearest approximation to the one we suppose now exists.

We will further assume that at a former period the shell was only 15 miles thick, the inner surface-temperature then being 3050° Fahr., and that from this condition the globe has gradually cooled down so as to possess a crust corresponding with the one accepted as now existant, namely 30 miles thick.

Leaving out of consideration for the moment the effects of denudation, we will assume that the outer surface of the globe remains of a constant diameter of 7912 miles*. The surface cannot be affected by contraction or expansion by heat, as its temperature varies only in response to external or climatic influences.

At 15 miles deep the crust, on its thickening to 30 miles, will have cooled from 3050° F. to 1550° F. Let us see what the circumferential contraction would be of a zone of rock at this depth.

For the sake of simplicity I will omit the varying expansibility of its component strata, and assume the effective contraction to be as determined by the mean of my experiments, namely 2·75 feet per statute mile for every 100° F. loss of temperature.

This would give 41·25 feet per mile linear contraction of a zone at the depth of 15 miles†, or 1,025,323 feet = 194 statute miles circumferential contraction of the globe. (Plate XVIII. fig. 2.)

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* 'Outlines of Astronomy,' Herschel, p. 560, 9th ed.; 7912·41 miles mean diameter, considered as a sphere.

† This is 7912÷2−15=3941 miles radius.

Plate XVIII.

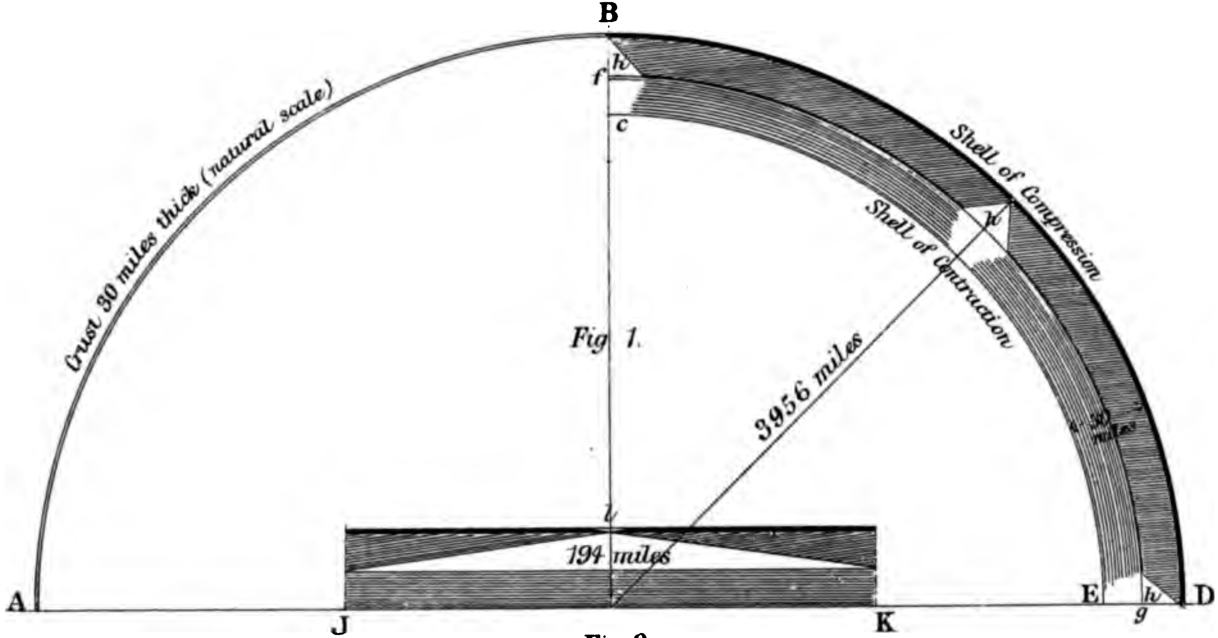

Fig 2.

MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

Sprague & Co Photo-litho. London

PLATE XVIII.

Diagram to illustrate the Effect of Secular Contraction on the Earth's Crust.

The Quadrant A B, Fig. 1, represents in true proportion to the radius of the circle a crust 30 miles thick.

The quadrant BD CE represents a crust 30 miles thick, but exaggerated in scale in proportion to the radius.

The line *f g* represents a zone, the temperature of which is assumed to have been formerly 3050° F., but which zone by secular refrigeration has cooled down to 1550° F., the zone of 3050° F. sinking to CE. The unshaded triangles *h*, *h* and space between the double lines *f g* represent in true proportion, in relation to the thickness of the crust, the contraction that the portion of the crust enclosed by B D *f g* would undergo by such a cooling.

On the hypothesis that the radial contraction for this amount of secular cooling would be 2·04 miles, the black line B to D shows the SHELL OF COMPRESSION; all below to *f g* being the SHELL OF CONTRACTION.

In nature the unshaded triangles below the "zone of flowing" would become filled by compressive extension of the rock, or, rather, the continuity of the beds would remain unbroken.

It is not definitely shown in this diagram what would take place below *f g*, but the hard part of the crust would form a continuation of the shell of contraction, as indicated by the unshaded portions.

JK, Fig. 2, is a section of a portion of the crust showing by an unshaded triangle the amount of contraction as above, for the whole of the crust 15 miles deep, if concentrated in one place, instead of being distributed in 8 triangles as previously assumed. The white triangle in the black band at *l* shows the total amount of compression due to the radial contraction assumed.

If the radial contraction of such a sphere for this amount of cooling were 30·8 miles, the lower zone of rock would be neither subject to compressive nor to tensile strain. If it were less, the strain would be tensile; if more, compressive.

What would the radial contraction amount to? Probably nothing comparable to this. The Rev. O. Fisher calculates that if the temperature of solidification were 7000° F., our globe would have radially contracted from the time of solidification to the present time 1·9 miles*.

It follows that if the radial contraction were fifteen times as much as Mr. Fisher calculates, the zone of rock at 15 miles deep would never at any time have been under compression.†

But we are not driven to dependence on Mr. Fisher's results; a little common-sense reasoning will show us that rocks at this depth, subject to the amount of cooling our Earth is assumed to have undergone, never could have been affected by compressive strain from such cooling.

It logically follows that if the radial contraction per mile is the same as the circumferential contraction per mile, there will be no strain at all set up in that part or zone of the crust where this circumferential contraction occurs.

It is also pretty clear that, as the heated globe is cooled from the exterior, the radial contraction must vary at every point in the radius, being least at the surface, greatest at a certain distance down, probably about the zone of 3000° F., and from that point decreasing rapidly until it is *nil*. It therefore follows, as the mean rate of radial contraction is less than the circumferential, that at the zone of greatest contraction the rocks will be subject to a tensile strain, but at the surface of the sphere to a compressive strain.

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* 'Physics of the Earth's Crust,' p. 72.

† "According to Mr. Mallet the diameter of the Earth is less by at least 189 miles since the time when the planet was a mass of liquid." Geikie, Text-Book, 1st ed. p. 286 (see Phil. Trans. 1873, p. 205).

Practically tension could not take place, as the superincumbent strata would by vertical compression elongate the rocks at the zone of greatest contraction to fill the vacuities that otherwise would be created.

But at what depth below the surface would tangential compression begin to act? This altogether depends on a correct determination of the radial contraction.

In the case assumed, at a depth of 1 mile, the loss of heat by secular cooling would be 100° F., and the circumferential contraction of the rocks at this zone 13 miles. With a radial contraction of 2·04 miles, the crust at this depth would be neither in tension nor compression. (See diagram, Plate XVIII. figs. 1 & 2, p. 123.)

These considerations have led me to think that there is a fallacy in the reasoning which attributes the corrugation of the Earth's surface to the contraction of the nucleus. If the above reasoning be valid, it is plain that whatever compression may take place in the crust of our globe must be confined to a very slight depth below the surface. To such a thin stratum in fact, that the ordinary denudations constantly going on would probably obliterate most of the resultant corrugations.

Nor must we forget, in estimating the value of this hypothesis in accounting for the phenomena of mountain-building, that, contrary to what should happen according to this hypothesis, the corrugations, foldings, and compressions of the strata of the Earth's crust increase with the depth to which they have been buried.

From these various considerations, I have arrived at the conviction that the cooling of our Earth has not extended to such a depth that we need consider the internal contraction as a geological cause.

In the course of ages, when it has run its course, and the crust has grown thicker and colder, the effects of contraction will become more sensible, and the shell of compression extend deeper into the earth. But this is a matter of the geological future which does not greatly concern us.*

ANALOGY OF THE MOON.

Fortunately, in attempting to discover the effect of secular refrigeration upon a cooling globe, we are not limited entirely to deductive reasoning. If, as astronomers and physicists aver, the moon is a dead planet, that is, has reached the final or nearly final stage of secular refrigeration, we can look to her for information as to the manner in which contraction affects the crust of a planet.

In 1875 I pointed out the geological distinctions between the Moon's surface and that of the Earth †, and showed that the physical features of the face of the Moon, which have been mapped with great accuracy, show a general absence of the effects of denudation such as characterize the Earth. This, it was considered, not only strengthened the view that our satellite possesses no atmosphere and no water now, but that if it ever had them, it must have been at a very early period and in a very small degree*. An attentive study of the maps of the Moon by Messrs. Nasmyth and Carpenter failed to disclose to me any trace of the well-known effects of denudation familiar to the student of the Earth's Geology.

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* Since writing this chapter I have, with the usual liberality of the American Government, received a copy of the 4th Report of the U.S. Geological Survey. I cannot resist quoting the following incisive lines by Capt. Dutton (p. 193).

"To this hypothesis there is a conclusive answer— indeed, a good many answers. The most direct one is as follows:—The very facts and line of argument which is relied upon to sustain a cooling globe proves, when pushed to its consequences, that the great interior of the Earth has not as yet undergone any sensible amount of cooling. The only cooling which that argument admits of has been located in a thin external shell not much thicker in any case than 150 miles, and much more reasonably not thicker than 80 or 90 miles. In short, the cooling would be only skin deep, while the nucleus is about as hot as ever. But by the terms of the hypothesis, if the nucleus has not cooled, it has not contracted, and the external shell has not collapsed in the way supposed. In short, the hypothesis is refuted by simply taking its data and postulates, and pushing them to their inevitable conclusions.".

† "The Moon and the Earth," Presidential Address, Liverpool Geological Society, 1875–6.

If therefore the Moon's features have been comparatively unaffected by external agencies excepting those of great changes of temperature between our satellite's day and night, and the cooling and consequent contraction has reached an advanced stage, it is natural for us to expect to find some pretty decisive indications of the way in which such contraction of the nucleus has affected the rigid envelope.

That portion of the Moon's surface which can be seen from the Earth is about four-sevenths of the whole. The class of features observable are four in number and consist of:—crater rings (with or without central cones, the largest of which have been called walled plains); mountain-chains with occasional isolated peaks; extended plains called "seas," with more or less irregularity of surface; cracks or fissures occasionally forming cliffs—one valley and bright radiating streaks.

The dominant forms are undoubtedly the "craters," which exist within a limit of largeness, but apparently without limit of smallness. Probably the next important features are the "mountains," of which there are a few isolated examples, but mostly they are collected into stupendous chains. In one of the grandest of these chains, it has been estimated that a good telescope will show 3000 mountains clustered together, *without approach to symmetrical order*.

It is remarkable that nothing in the shape of foldings are detectable by the telescope. If such had resulted from the crushing-in of the solid envelope, we should expect to find some of the principal craters, which measure from 20 to

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[*] Ericsson has put forward the novel theory that the "ring-mountains" in the Moon are formed of ice from the congelation of steam arising from crater-ponds, and estimates that "the sum total of water on the Moon amounts to 2,028,600 cubic miles."—'Nature,' July 15, 1886, p. 251.

80 miles across, deformed by such foldings. Apparently nothing of the sort has occurred, at all events the effects are not discernible. In Plate XIX. is reproduced, by permission, Nasmyth and Carpenter's excellent view of the Lunar Apennines, the crater Archimedes, &c. In whatever way these mountains may have been built up, they are, it is evident to the geological eye, quite dissimilar to mountain-ranges on the Earth produced by lateral pressure and folding.

So far as we can see, the strains which have occurred in the Moon's solid envelope have been relieved by fissures and cracks. The broken appearance of the surface, and some of the ridges, may be due in part to lateral pressure. The enormous number and size of the lunar craters probably arises from the relief of the strain taking the form of emission. The lava may have welled-up by the falling-in of the crust—such welling-up keeping large portions of the crust molten.

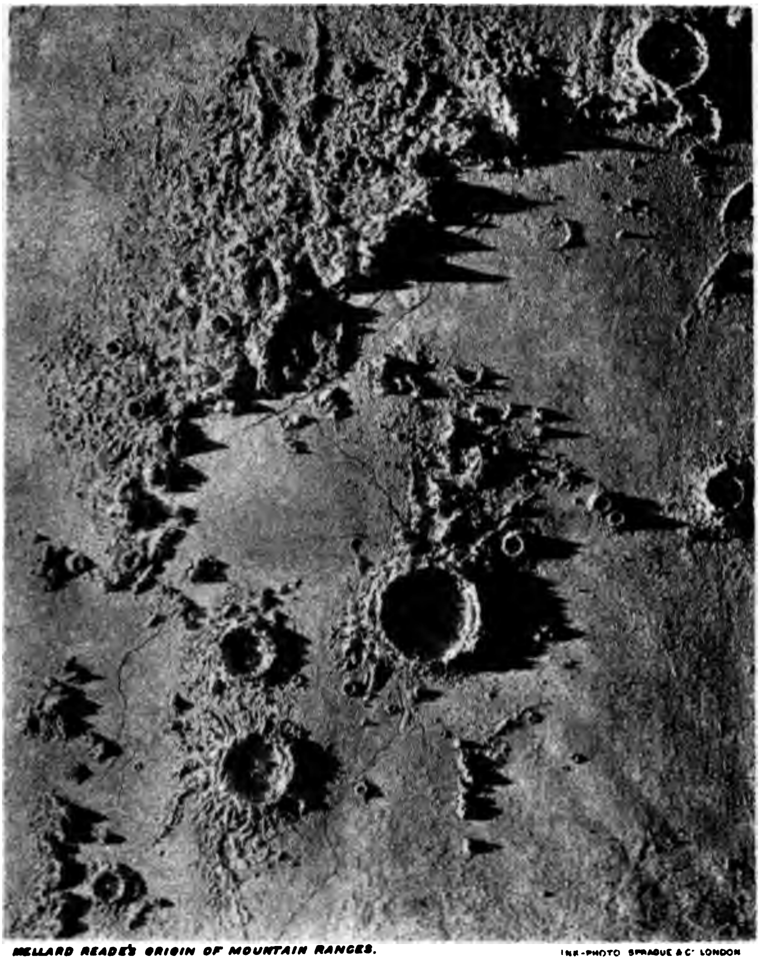
As pointed out by me in the Address referred to, if there has been no denudation of the Moon's surface such as takes place on the Earth, sedimentary deposits could not have been laid down. No evidence of such deposits are indeed discoverable, and we have good reason to believe they do not exist on the Moon's surface.

If horizontal pressure and folding as here maintained is intimately connected with sedimentation as cause and effect, the explanation of the absence of such structures in the Moon's physiography as are exhibited in mountain-ranges, is at once explained.

PLATE XIX.

The Lunar Apennines, Archimedes, &c., from 'The Moon considered as a Planet, a World, and a Satellite,' by Nasmyth and Carpenter. A comparison of this with a shaded map of a mountain-district like Switzerland (the Alpine Club Map for instance, published by Messrs. Longman), will show how dissimilar these reliefs are to those of the Earth which have been produced by horizontal pressure.

Plate XIX.



MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

INK-PHOTO SPRAGUE & Cº LONDON

CHAPTER XII.

OTHER THEORIES OF COMPRESSION BY GRAVITATION.

It is evident that the motive force invoked by the theory just examined is gravitation—the gravitation of a rigid shell towards a shrinking nucleus. The introduction of a plastic or molten shell between the upper rigid crust and the solid centre in no wise affects the argument as to the incompetency of contraction by loss of heat to produce the phenomena of mountain-building.

Mr. O. Fisher has suggested an additional source of contraction in the loss of water, which he thinks takes place in the form of steam emitted by volcanoes. As it is a debatable point whether this steam is derived from water which has found its way downwards from the surface or is initially contained in the molten magma, it would seem an insecure hypothesis on which to base a theory of contraction. Even if we grant that every jet of steam which ever issued from a volcano were so much matter taken from the Earth's interior, it would appear to me, from the following considerations, to to be quite inadequate to provide sufficient contraction for the development of mountain-ranges by tangential stress.

If we consider that the oceanic waters only average about 2½ miles deep according to the latest calculations, and certainly would not exceed a mean of 2 miles if distributed over the whole globe, we have a gauge wherewith to measure the extent of such possible contraction, for unless the volcanic steam were drawn off into space, the ocean must on the hypothesis be the receptacle for it when condensed.

If this oceanic water were *all* derived from the interior—a very violent supposition—it would, the bulk remaining constant, provide for a radial contraction of from 2 to 2½ miles. Therefore the contraction would be inadequate, unless we imagine the matter of the Earth's interior to be in a state of great distention by superheated steam, a supposition that is negatived by its great specific gravity *.

Mr. Osmund Fisher, since suggesting this hypothesis of contraction, after further examination finally rejects it †, and in lieu thereof substitutes the following theory :—

He considers that if the crust, estimated at 25 miles thick, resting on a fluid substratum, fissures at the bottom, such fissures may become filled with superheated steam, which will exert sufficient pressure on the walls of the rents to account for the lateral pressure to which we find the Earth's crust has been subjected ‡. The objections to this theory are serious. There is no geological evidence that any such deep fissures were ever formed, for, as will be explained further on, it is improbable that volcanic dykes originate at such a vast depth, and still less that the spaces they fill were ever occupied with anything but solid matter.

Anyone who has had practical acquaintance with steam will, I think, negative the view that vapour could exist in the earth on a large scale at a tension sufficient to exert greater effective lateral stress than is due to the actual weight of overlying rock. The presence of such high-tension vapour is inconsistent with the existence of the globe; it would burst [*].

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* There seems no reason to suppose that there is more water on the Earth now than in former geological periods, which there would be if steam from the interior of the Earth were constantly being condensed. Many physicists consider that the water of the ocean is, on the contrary, being used up in hydrating the cooling crust, and point to the Moon as a final example of this process. Neither proposition can be proved.

† 'Physics of the Earth's Crust,' p. 183.

‡ Ibid. p. 186.

None of the theories already examined provide quantitatively an adequate explanation of the compression we everywhere see was the accompaniment of mountain-building.

But there is yet another theory which calls in gravitation as the compressive force. I allude to that proposed by Mr. W. B. Taylor [†], who assumes that at one period the Earth had four times its present rotational velocity, and an "equatorial protuberance 396 miles higher than at present," while "the poles would have been about 658 miles nearer the centre of the Earth than they are at present" [‡].

We may at once admit that this is invoking a tremendous compressive force which would affect almost every part of a solid globe. As the rotatory velocity decreased such a globe would, in assuming the form due to its velocity, compress its constituent rocks at the equator, and bulge them out at the poles.

The theory seems, however, to possess the weakness common to most of such suggestions. It does not explain the phenomena as nature presents them to us. Mountain-ranges are not all meridional in their direction, which would apparently be the case if they were created in this manner [§].

Nor does it explain why mountains are invariably built out of great thicknesses of new sediments. It is purely a physical, not a geological theory.

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[*] A *précis* of Mr. Fisher's views is given in Mr. Jukes-Browne's 'Handbook of Physical Geology,' a work containing much new and well arranged matter.

[†] "On the Crumpling of the Earth's Crust," 'American Journal of Science,' Oct. 1885, pp. 249–266.

[‡] Ibid. p. 257.

[§] If not all meridional there would exist a successive symmetry of position that could not have escaped notice.

CHAPTER XIII.

APPLICATION OF THE THEORY OF LOCAL EXPANSIONS OF THE EARTH'S CRUST TO EXPLAIN CHARACTERISTIC FEATURES OF MOUNTAIN STRUCTURE.

INSTANCES OF COMPRESSION AND MOVEMENTS OF ARCHÆAN ROCKS.

We are now in a position to examine in detail whether the expansion of rocks by heat does not afford a better explanation of all the phenomena of mountain-building than any imaginable compressive force originating in gravitation.

In the first place, a little consideration will convince us that expansion by heat will affect equably every particle and molecule of matter in the rocks.

The internal strains set up in a stratum expanding, but unable to lengthen itself laterally in consequence of its being buttressed up by the surrounding portions of the Earth's crust, will be distributed throughout the whole expanding mass.

If, on the other hand, the force were applied at the ends of the stratum as a compressive strain, instead of through every particle as by heat, the result would be a crushing at the ends where the pressure was applied.

But under certain conditions, crushing may follow from expansion, as we shall see further on.

Repeated Compression of the Lowest Rocks in the Geological Series.

The researches of modern geologists have shown that the earlier rocks have been the most powerfully affected by compressive strains. The gneisses and schists which seem to underlie all the Palæozoic sediments, give evidence of the repeated application of compressive forces.

It is not my intention to enter into the Archæan controversy further than to note that when gneiss and true schist appear in *great masses*, it seems to be *prima facie* evidence that they are older than the oldest Palæozoic rocks. The manner in which the newer strata are often involved in the folds of these older rocks and metamorphosed, had led geologists, who thought they were applying the principles of Hutton and Lyell, to confound them together, and assign the age of the involved rock to the whole mass.

An attentive study of the abstracts from the writings of various authorities on mountain-structure, given in previous chapters, and, as far as was possible, in their own words, will show that in *every* case the newer sediments lie geologically upon gneissose and schistose rocks when not on granite or granitoid rock. Such gneissose and schistose rocks never rest on the newer rocks except through the agency of great folds and displacements.

I admit this, knowing at the same time that it is considered by some excellent geologists to be a heresy. Admiration for the principles of Geology as expounded by Hutton and Lyell, must not, however, blind one to new truth. Science is progressive; we see but a little way at a time; we make generalizations which include all the then known phenomena. After a while we find some stubborn fact of nature that refuses to range itself on the side of our generalization. The generalization may not be wrong; on the contrary, it may be perfect up to a certain point: that is, true with limitations. A new set of phenomena may come in to limit our generalization.

If wise, however unpalatable it be to us, we accept the fact, and take a fresh departure.

This, I take it, is what has occurred in Geology. I must guard myself against being supposed to accept the doctrine that microscopic lithology is to take the place of palæontology in fixing the age of the older rocks. I fancy there are but few who take so extreme a view, and they are enthusiasts *.

Still little is done without enthusiasm; it is the lever that moves the world. Certainly it is due to the labours of an ardent band of geologists of a new school, that the true succession of the Highland rocks has been approximately discovered.

That gneissic rocks, such as are found in the Highlands, could not succeed Palæozoic rocks in geological sequence, was the contention of those who doubted that the accepted Murchisonian succession was the correct one. This led to fuller inquiry and more careful examination by those who

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* Since the above was written, Mr. G. F. Becker has in the 'American Journal of Science' (May 1886, pp. 348–357) described some metamorphic rocks of California which are considered to be of Cretaceous age.

Mr. Becker states that all the more important minerals of the Archæan schists are found in the metamorphosed rocks of the Coast-Ranges, but the quantitative relations are different, especially those of the felspars, plagioclase being more common in the Coast-Ranges, while orthoclase predominates in the Archæan.

There is far less evidence of pressure than in Archæan areas, and the intensity of the chemical actions has been much less uniform; "but it is evident that under conditions not greatly dissimilar to those which prevailed in California at the close of the Neocomian, rocks not distinguishable from those of the Archæan areas might have been formed."

The depth at which the rocks now exposed were buried at the epoch of metamorphism was probably 2000 to 3000 feet. They show little indication of moulding by pressure, but "the amount of fracturing is really astonishing."

I do not consider that this very interesting information in any way invalidates the general principles stated above; the lesson I should draw from it is rather that it is unnecessary to invoke extraordinary agencies for the original production of the Archæan schists, and in this respect it supports the great principles of Geology established by Hutton and Lyell.

favoured what are called Archæan views of Geology. So far the result of the Highland inquiry has vindicated the views of this school, as opposed to those of Murchison. It was then found, as so well explained by Prof. Judd [*], that the late Prof. Nichol had anticipated by a good many years some of the now accepted views of the order of succession of the Highland rocks. It was, however, through the labours of Dr. Charles Callaway and Prof. Lapworth that the demonstration first came, which has been accepted by the Survey. The knowledge of the great foldings, thrust planes, and reversed faults which distinguish the north-western part of the Highlands of Scotland has been since much extended by the labours of Messrs. Peach and Horne, as shown in the clear exposition of Dr. Arch. Geikie [†].

These discoveries are so intimately connected with the knowledge we now possess of the extraordinary foldings which have taken place in the building-up of mountain-ranges that it was impossible to avoid alluding to them.

In a paper on the "Newer Gneissic Rocks of the Northern Highlands" [‡], Dr. Callaway clearly demonstrated, by acute and conclusive reasoning, based on careful examination, that gneiss of Archæan age, called by him "Caledonian gneiss," is found resting upon members of the "Assynt series," which are of Silurian age. This is shown (pp. 403–4) in both a dip and strike section of Ben Arnaboll.

He also clearly showed that the several members of the Assynt series are frequently folded back upon those below, so as to produce the impression of geological succession in the beds. In this way the difficulty of the supposed existence of *two* quartzites was surmounted, and the way paved for the acceptance of the new views.

The demonstration of the fallacy of the accepted classification of the rocks depended altogether upon the actual tracing of the overthrown beds along the folds. If this had been done thoroughly, even in the time of Murchison's influence, it is questionable if his views would have prevailed. It was a very difficult piece of geological surveying, which could only be accomplished by great labour and pertinacity in the field. Would this labour have been undertaken, or the difficulties overcome, had not the authors been under the enthusiasm of an idea?

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[*] Address Geol. Section British Association, 1885.

[†] 'Nature.'

[‡] Quart. Journ. Geol. Soc., August 1883, pp. 355–414.

While waiting for the confirmation or disproof of the further views of the Archæan geologists, we cannot refuse them the meed of praise for helping to put the geology of the northern Highlands on a sound basis of fact.

And here I may express my opinion that the new views are not opposed to the Huttonian principles of Geology. Some of the early generalizations may have to be modified, but they are too deeply founded in truth to be destroyed.

Prof. Lapworth, surveying an adjoining area at the same time, arrived at pretty much the same result as Dr. Callaway. In a paper contributed to the Geological Magazine, entitled "The Secret of the Highlands," * he showed very conclusively, by a comparison of the foldings and faults of the Highland rocks with those of the Alps, as figured and explained by Heim, that the whole area is the denuded remnant of a great mountain-chain.

That these folds, overfolds, overthrusts, reversed faults and normal faults, fractures, fissures, and crushings, are not the effect of one series of lateral movements, as is usually assumed, I hope to show. On the contrary, I venture to maintain that they are due to repeated lengthenings of the strata over immense areas by expansion and consequent local compression, combined with repeated faultings through contractions of the strata in masses during cooling and loss of heat.

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* 1883, pp. 120, 193, 337.

A mountain-chain may be due to one series of such combined, though successive earth-movements. Or it may have been created by a repetition of such disturbances at different geological periods.

Instances of Repeated Compression.

Prof. T. G. Bonney, in a short but most interesting and suggestive paper in the Geol. Mag. for November 1885 (pp. 494–496), entitled "Preliminary Note of some Traverses of the Crystalline District of the Central Alps," shows that "the principal metamorphism of the crystalline series was anterior to the Carboniferous." The proof of this lies in the fact that the conglomerates which often occur at the base of the non-crystalline series contain fragments of the crystalline rocks undistinguishable from the parent rocks.

In the heart of the principal Alpine chains, and seemingly at the base of everything, are coarsely crystalline gneisses apparently differing little from granites, except that they generally exhibit a certain foliation, and occasionally seem to be interbedded with thin seams of micaceous schists or flaggy fine-grained beds.

On examination, these latter beds appear to be generally due to crushing. Their strike agrees with the apparent foliation of the older crystalline rocks, and with that present in the newer crystalline rocks. This corresponds with the strike of the main physical features of the district, and with the cleavage of the included troughs of sedimentary rocks. It runs for great distances with a remarkable uniformity, and does not materially vary from W.S.W.–E.N.E.

This apparent foliation is due to the development of extremely thin films of a micaceous mineral. Although often bearing the aspect of a highly micaceous schist, on examination in a transverse section it is distinctly seen to be a crushed gneiss; though conspicuous, it is a mere varnish.

To this surface Prof. Bonney gives the name of "Sheen Surface."

It is a kind of "cleavage foliation,"—that is, a foliation due to cleavage and subsequent to it. Although from certain points of view so conspicuous, its remains often constitute a very small part of the mass of the rock.

The pressure which has produced the "sheen surface" has in many cases affected the orientation of the minerals, which are present in the true "foliation" layers of the more distinctly foliated or mineral banded rocks. It has affected these minerals, as pressure affects the constituents of a sedimentary rock. Very commonly the sheen surface corresponds with the original foliation-surface; it may, however, be seen in some cases crossing the foliation at all angles. It behaves, in fact, as cleavage in slates does with regard to bedding.

Prof. Bonney, who has made the study of crystalline rocks a speciality, concludes that a non-foliated rock may be rendered to some extent foliated by pressure followed by a certain amount of mineralization. Thus some gneisses may be formed by crushing from granites, some schists out of other igneous rocks. "It may obliterate an earlier foliation or it may intensify it, or it may produce an independent and more fissile foliation." *

In this sense gneiss may be said to pass into granite, and these superinduced changes are no doubt responsible for the views held by some good geologists that granites may be of metamorphic origin.

Proceeding outwards from the central granitoid masses of the Alps, we come on gneisses and schists where the evidence

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* In his late Presidential Address to the Geological Society, Professor Bonney has expanded some of these points. He considers that he can distinguish between stratification-foliation, or foliation obscurely indicating the bedding-planes, and a secondary or cleavage foliation, initiated at a much later date—"post-Secondary and probably post-Eocene."—Q. J. G. S., May 1886, pp. 99 and 107.

of some kind of stratification is more marked, "bands of crystalline limestone, quartzite, and granulite being associated with mica schists of many kinds—simple, garnetiferous, staurolitic, actinolitic and the like—the bands of different mineral character and composition, varying from mere streaks to layers many yards in thickness." They are, in fact, associated exactly as limestones, sandstones, and clays are associated in the ordinary sedimentaries. This is a most concise and lucid description of the crystalline rocks, which form the axes of so many great mountain-ranges. It enables us to understand the various changes necessary for their genesis.

Dr. Callaway is of opinion that in some cases the apparent foliation of granite is really the fluxion structure impressed upon it by lateral pressure during consolidation. The foliated granite of Northern Donegal, mistaken by some for Laurentian gneiss, he considers has been produced in this way. Included blocks of diorite are unaffected by the foliation. Had the foliation been impressed upon the granite after consolidation, he thinks the diorite would have become foliated also*.

That the main characters of the Crystalline rocks—gneisses and schists—were impressed upon them before the pressure which folded them with the overlying Silurians was applied, is Dr. Callaway's opinion as well as Prof. Bonney's. He tells me he finds no distinguishable difference between the boulders of Crystalline rocks in the Palæozoic conglomerates and the parent rocks from which they come†.

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* "On the Granitic and Schistose Rocks of Northern Donegal." Q. J. G. S. May 1885, p. 230.

† According to Emmons the crystalline rocks are of igneous origin, and owe their banded structure to an arrangement of their mineral constituents by movements while yet in a liquid state, so that gneiss may be defined as a laminated granite.—Sterry Hunt, "Report on Azoic Rocks of S.E. Pennsylvania," Second Geol. Survey of Pennsylvania, 1875, p. 44 E.

Flowing of the Crystalline Rocks.

If the rocks forming the cores of such ranges as the Alps were crystalline before the upheaval of the mountains, it is quite evident that, hard and rigid as they were, they must have responded to the subterranean pressures, and *flowed* like lead through a die. In no other way does it seem possible to account for the forms these crystalline rocks have assumed.

Mr. Clarence King gives some interesting evidence of the effect of pressure on the Archæan rocks of the Rocky Mountains*. "In connection with these post-Cretaceous folds over the Archæan bodies are some interesting effects of compression and distortion of the central Archæan mass." "From the modern positions of these old shore-lines it is seen that the Archæan body suffered in the post-Cretaceous orography, not only an irregular uplift, resulting in vertical waves, but a true torsion by which the body of the island has actually yielded to a twisting force, amounting in some places to a shear of 3000 feet." . . . "In yielding to this force the Archæan bodies have developed an amount of plasticity which, in view of their crystalline nature, is very surprising."

Mr. King also states that these Archæan Rocks "were altered into their present crystalline condition prior to being folded up into mountain-ranges. This is proved from the fragments of the bedded schists that are enveloped in plastic granite, which appears as distinct intrusions in rifts and fractures of the crystalline beds, caused at the time of their folding or upheaval."

The phenomenon of "fan-structure," which is well shown in Heim's Section of the Central Alps (Plate XIV. fig. 1, p. 98), is a clear proof that these crystalline rocks have "flowed" under pressure to an enormous extent. The

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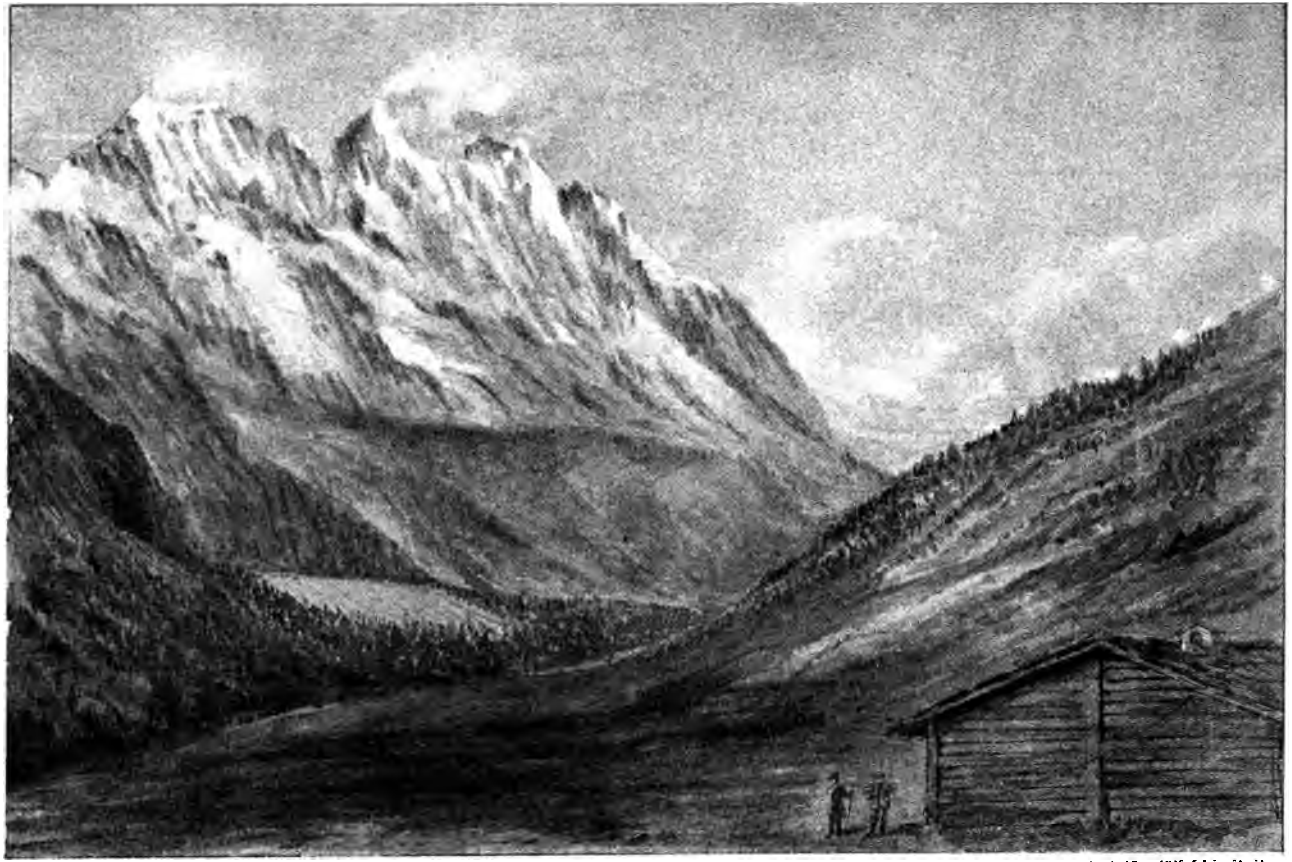
* Geol. Exploration of the 40th Parallel, vol. i. pp. 51–2.

Plate XX.



MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

[illegible] MACLURE & C° LONDON

MONT-BLANC MASSIF *from the* ALLÉE BLANCHE.

PLATE XX.

View of Mont-Blanc Massif from the Cantine in the Allée Blanche
(from a sketch in 1867).

The bottom of the valley consists of Jurassic strata enclosed in a fold in the crystalline rocks. In the valley of Chamounix, on the opposite side of the massif, the Jurassic rocks are similarly enclosed in a fold. (See map of Switzerland, Plate XIII., p. 97.) All the Mont-Blanc massif consists of crystalline rocks, forced up in a fan-like form in a similar manner to that of the St.-Gothard (Plate XIV.). As can be seen on reference to the Map, it is in reality a continuation of the same crystalline core—an elongated dome, pushed up into or through the Jurassic and later rocks, since denuded.

Saussure, as pointed out by Daubrée, was the first to observe that the massif of Mont Blanc was divided into large foliations, having their planes parallel to each other and parallel to the direction of the chain. These foliations, which are nearly vertical in the centre, are inclined at the sides, dipping symmetrically towards the axis, so as to present in transverse section the appearance of an open fan. Protogene forms the central mass, and passes gradually into gneiss and talc-schist, which envelop it to a great thickness, except on the south side (Allée Blanche). The crystalline rocks are thrown over the stratified Jurassic like as if the Jurassic had been pushed into a cleft in the middle of them, in the shape of a button-hole, as expressed by Elie de Beaumont. "The same structure has been recognized in the St. Gothard, the Bernese Alps, the Pyrenees, and elsewhere." Some of the minerals were crystallized before the rocks were foliated, such as mica, orthoclase, oligoclase, &c.; while some, which lie across the plane of foliation, must have been formed afterwards; but even some of these are bent and broken by after-movements. All these facts tend to show that slow movements went on for a long time, affecting the whole interior of the rock posterior to the production of the foliations.

It is interesting to compare the section of the Central Alps (Plate XIV. fig. 1) with the generalized section of the Eastern Alps by Sedgwick and Murchison, in their admirable paper on the "Structure of the Eastern Alps" (Trans. of the Geol. Soc. 1832). A similar central core of crystalline rocks appears with the sedimentaries arranged on either flank, but, as is usual in mountain sections of this early date, no foldings are exhibited.

St. Gothard massif was originally one of these vertical horseshoe loops—so also was that of Mont Blanc. It is difficult to see how such a form can be explained except by "flowing." The rock has seemingly been forced upwards, and has flowed from between the advancing jaws of the tightly compressed sedimentary folds.

Again, where the interior mass of an overfold is composed of crystalline gneiss, such as is figured in Dr. Callaway's section across Coniveall, the only probable explanation is that the rock has flowed*. I use the term "flowed" to distinguish the movement from that of the "folding" of regularly stratified beds, which are subject to strains of a more complicated and composite nature, one part of a bed being extended, while another part is thickened by lateral compression. Another part may be subject to tension or compression in bending; the whole being, in one way or the other, repacked and adapted to their altered conditions of space.

The geological structure of the Northern and Middle gneissic regions in Pennsylvania is described by Rogers as presenting a series of closely appressed folds, most clearly seen in the South Mountain, where, from one end of the range to the other, the gneiss and the older Appalachian strata in contact with it are bent into a series of folded or inverted flexures† (see Plate IX. p. 42). But Prof. H. D. Rogers elsewhere remarks that "the gneiss in many localities has no symmetrical foldings, but only a broad outcrop with a definite dip"‡. Such is the difficulty in interpreting a district like this, that Prof. Lesley, in comparing

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* Q. J. G. S. 1883, p. 383.

† Second Geol. Survey of Pennsylvania. Azoic Rocks of South-eastern Pennsylvania, by Sterry Hunt. 1875. Part I.

‡ "The Azoic System and its Subdivisions," by J. D. Whitney and M. E. Wadsworth. Bulletin of the Museum of Comparative Zoology, Harvard College, 1884.

Mr. Hall's views with those of Mr. Rogers, says that Prof. H. D. Rogers was guided everywhere by a theory of parallel anticlinal folds in the great Azoic or Hypozoic strata; and of intermediate synclinal troughs, some of them wide and deep, others narrow and shallow, but all of them containing preserved remnants of a more micaceous strata of a later age*; while Mr. Charles E. Hall arranged the rocks in the same region in irregular areas. Prof. Lesley says, also, "Since 1858 the district in question has been closely and repeatedly investigated by Prof. Frazer and Mr. Hall, the one approaching it from the West, the other from the East. They differ radically in their views of the order and superposition of the formations, not only from Prof. Rogers, but from each other"†. Mr. Persifor Frazer, describing the Northern gneiss-region, remarks "that the wide area of gneiss now under description is undulated in a succession of anticlinal and synclinal waves is obvious to any practical geological observer who studies its structure with due care;"‡ and, "There, as we have already seen, several long tapering tongues of the gneiss formation project forward towards the west, including between them actual troughs of the Palæozoic rocks, a feature not attributable to any other mode of elevation of the gneiss than that of an undulation of its general floor, in the manner of long anticlinal waves. Some of these waves, no doubt, are so closely compressed or folded, and others are so irregularly dislocated as to render the analysis of them obscure or even impossible, yet the geology of the country clearly establishes their presence"§.

In a series of excavations for iron ore a succession of parallel dislocated synclinal axes, of which the presence on the surface was not manifest, enabled Mr. Frazer to prove these undulations in the gneiss.

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* "Geology of Chester County," Second Geol. Survey of Pennsylvania, 1883, p. 52 C^4.

† Ibid. p. 34 C^4.

‡ Ibid. p. 165 C^4.

§ Ibid. p. 166 C^4.

In each of these "clefts or deep narrow troughs is a belt of red sandstone of Mesozoic age dipping S.E. These strata of red sandstone are invariably highly altered and crystalline, for they frequently contain minute crystals of mica, specular iron ore, graphite, and even felspar. Yet in other layers of mottled and half-baked red shale, in close alternation with these more altered ones, we see proof of their unquestionable identity in composition and origin with the red sandstone formation, from the general southern margin of which some of them are separated by an interval of four miles."

Mr. Fraser says of the Southern gneiss region:—"Whatever may be the age of the rocks of this region they were originally sediments of mud, sand and gravel, for they are everywhere more or less distinctly stratified, although it is sometimes difficult to distinguish their original bed-planes from the planes of cleavage which cross them (usually in nearly vertical planes), and in many cases completely mask them. This is especially true of their more massive layers. But the real stratification is visible wherever they are quarried."*

A very excellent idea of the crumpling and crushing these formerly deep-seated crystalline rocks have undergone may be obtained from the autotype picture of the contorted or convoluted gneiss of Wissahickon Creek facing p. viii C^4 of the "Report on Chester County" referred to. The looped crumpling of the plainly banded structure shows plainly the kneeding-up this crystalline rock has undergone.

Prof. J. J. Stevenson, in his Report on the Geology of a portion of Colorado †, describing the passage of gneiss into granite, says :—"On the Currant Creek, a tributary of the Arkansas, the changes are very prettily shown. There the mica-schist becomes a schistose gneiss containing numerous segregations of the granite of large size, together with immense numbers of the little nodules already mentioned.

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* "Geol. of Chester County," 2nd Geol. Surv. Pennsyl. 1883, p. 37 C^4.

† Explorations West of the 100th Meridian, vol. iii. p. 348.

The gneiss gradually becomes more compact, and at last is lost in the granite." "The transition from mica-schist to granite and from hornblende-schist to syenite is shown quite frequently, and the rocks of one series readily give place to those of the other."

Mr. Stevenson also describes the gneiss in the vicinity of the syenite granite on the North Fork of the South Platte as beautifully waved and cleaving readily along the curves, causing here and there overhanging arched cliffs whose under surface is a thin layer of mica. These curves appear not to be parallel to the bedding, and therefore the result of foliation. "On the first ridge west from the river, the gneiss becomes a mottled schist with little felspar and many pebbles of quartz, while further on the whole becomes a felspathic granite almost without mica" *.

Mr. S. F. Emmons, describing the Wahsatch Range, says it presents a type of extreme complication, contrasting strongly with the simplicity and regularity of its nearest neighbour the Uinta Range.

The simplest expression of their structure would be that of a sharp north and south anticlinal fold over pre-existing ridges of granite and unconformable Archæan beds, *whose axis has been so bent and contorted by longitudinal compression* that it at times assumes a direction approximately east and west †.

Again, describing the Farmington Archæan body ‡ Mr. Emmons says :—"The lowest exposed members are a great variety of mica and hornblende gneisses and schists, together with a few granitoid beds, and some limited quartzite and slates. The main series is composed of a varying family of gneisses; the lowest of these are very coarse, composed of large crystalline masses of flesh-coloured felspar and partially decomposed, earthy brown mica and large milky-white irregular bodies of quartz. This rock is interesting as showing the transition from an evenly bedded rock into a structureless one. The original sheets of mica may still be traced through the rock, but they are twisted and broken and crowded into such positions that at first the rock looks like a very coarse granite. This same transition between schist and structureless rocks, the result of pressure, is also noted in the East Humboldt Range, Nevada." "It would seem, from the results of irregular pressure, both here and in the East Humboldt Range, that the schistose structure can be easily broken up by lateral pressure, and that a distinctly bedded rock may be easily compressed into one which possesses no evidence of bedding except its being banded above and below by distinctly stratified rocks, and that the result of this compression may *act very unequally in different* zones of the same series, giving rise to the appearance of an eruptive rock lying between two members of a stratified series. That they are not eruptive rocks is clearly to be found by following them out in the strike, when they may almost always be traced into distinct stratification." *

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* Explorations West of the 100th Meridian, vol. iii. p. 350.

† Ibid. part ii. p. 341.

‡ Ibid. part ii. p. 378.

Mr. Arnold Hague, describing the northern region of the West Humboldt Range, says:— "Along its northern and western edge the granite mass is overlaid by a series of metamorphic schists and of light-coloured mica-gneisses in turn overlaid by a fine white knotted schist. The strike of these beds is north 38° east, standing nearly vertical. The contact of the granite and schists is extremely interesting, showing in horizontal plane an irregular angular intrusion of the former into the latter outlying masses of schist lying in the granite and extending as promontories from the main mass of schist for 400 or 500 feet.

"The line of demarcation between the two bodies is easily observed, and there seems to be a tendency of the schist to pass by gradations into the granite itself.

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* Explorations West of the 100th Meridian, vol. iii. pp. 379–80.

"The granite is here traversed by structural planes having a strike parallel to the bedding of the schist; there is also another set of lines approximately at right angles to the former." *

Mr. Clarence King, describing the Archæan core of the Colorado Range, says that the "ideal axis in elevation was a deeply undulating line. From longitudinal pressure it was also deflected in plan into horizontal sinuosities, and consequently the sides of the anticlinal were alternately thrown into broad convex folds or recurved in broad reëntrant bays, in which the beds were severely crumpled in secondary folds or confusedly dislocated."

Added to these disturbances was a third series of effects, resulting from forces that tended to warp the anticlinal, introducing an irregular shearing, which complicated not only the main folds but the secondaries. As a result there is one broad central fold with numerous parallel subordinate axes, whose corrugations probably do not penetrate deeply into the strata; Mr. King considers these movements took place after the crystallization of the rocks themselves and anterior to the deposition of the Cambrian †.

In these districts the distinction between the Archæan and later sedimentaries is so marked and the unconformity so great that it is impossible to mistake one for the other. *The locus of greatest disturbance is also where the sedimentaries were in greatest force and thickness.*

After the uplifts of the Wahsatch Range took place, and the Palæozoic and Mesozoic strata were thrown into their present inclined position, a great longitudinal fault occurred throughout the explored portion of the range by which the entire western half of the ridge was thrown downward from 3,000 to 40,000 feet, and it is now entirely buried beneath the Pliocene and Quaternary formations of the Salt-Lake basin.

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* *Loc. cit.* p. 715.

† "Systematic Geology:" Geol. Explor. of the 40th Parallel, pp. 21-2.

The present abrupt west front of the Wahsatch is the standing face of this great fault, and here the Archæan rocks are seen to occupy the core of the range, unconformably underlying the Palæozoic series, and rising to different stratigraphical horizons in the overlying series.

In the Cottonwood Cañons 30,000 feet of approximately conformable Palæozoic strata overlie the Archæan granites and schists *.

There are in various parts of the globe enormous areas of these gneissic and schistose rocks. They cover in North America a large part of the continent from the Arctic Circle to the Great Lakes, in addition to those in the mountain-areas described. Not only do they form the cores of the Himalayan Ranges but they occupy in Peninsular India a continuous tract 1400 miles long with a mean width of 350 miles, extending from Cape Comorin to Colgong on the Ganges. In addition they occupy a considerable area in Bundelkand, and the Arvali ranges are formed of them †.

In Scandinavia they occupy extensive areas. In the South Island of New Zealand the most ancient Palæozoic rocks are underlaid by vast masses of crystalline foliated rocks, and similar rocks are found in Australia.

Their distribution is world-wide, and wherever the geological relations have been worked out there is always a marked unconformity between these crystalline rocks and the overlying sedimentaries. Mr. G. K. Gilbert, in his very excellent notice of Dr. Geikie's 'Text-Book of Geology,' insists upon the profoundness of the chronological break, and says "there is no known locality where a newer formation rests conformably upon the Archæan. There are few where the discordance of dip is not great. There are few where the superior formation is not relatively unaltered, and none where the inferior formation is not highly meta-

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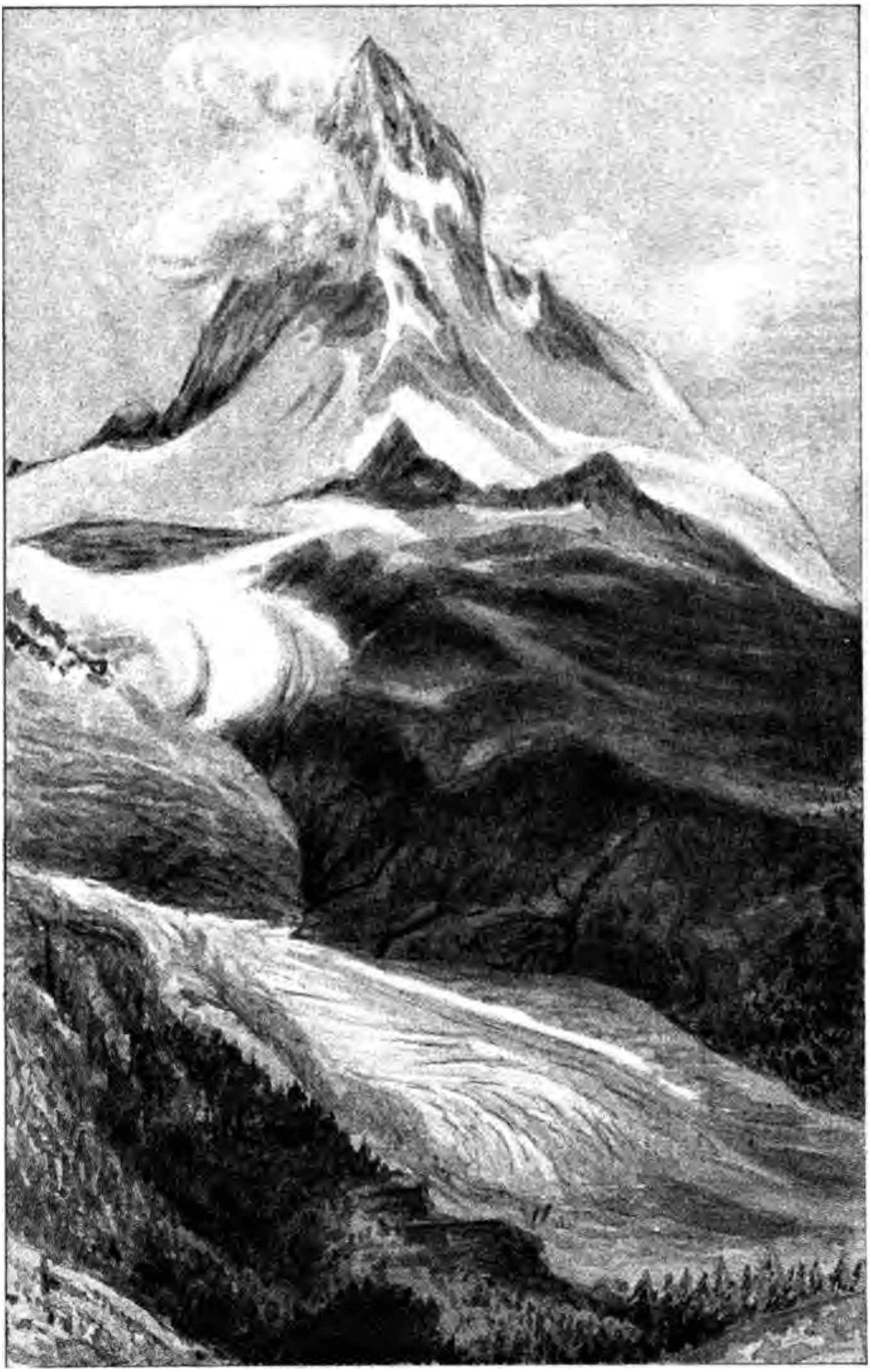
* "Systematic Geology," *loc. cit.* p. 44.

† 'Manual of the Geology of India,' part i. pp. 4–5.

Plate XXI



MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

THE MATTERHORN.

PLATE XXI.

View of the Matterhorn (Mont Cervin), from a point halfway between Zermatt and the Riffel Hotel (from a sketch in 1869).

The great Gorner Glacier is seen flowing in the foreground between walls of crystalline rock, below the level of the observer. This eastern face of the Matterhorn is in outline like a shark's tooth. It stands in isolated grandeur above the general level of the Alpine ridge like a huge pyramid. The view from La Breuil showing the southern face, and a profile nearly at right angles to the one here represented, is remarkably different in outline, and, though pyramidal, would hardly be recognized as that of the same mountain.

The whole of the peak, according to Signor Giordano, consists of an apparently regularly bedded series of serpentinous and micaceous schists, and of greenish-grey gneisses. There is no doubt that this striking natural pyramid has been cut out of a much larger mass of crystalline rocks by atmospheric denudation, and its form determined by internal structural lines, probably joints. The outline of Monte Rosa, part of the same massif, and several hundred feet higher than the Matterhorn, is of a rounded character.

An examination of a well-shaded map of the Alps exhibiting their relief, shows the remarkably sharp ridgy character of the ranges. Signor Giordano says that the sharp-peaked form of Mont Cervin has been produced by the comparative indestructibility of the harder gneissic rocks of which it is composed, the foliated calcareous schists of the base, seen in the Val Tournanch in which it stands, being more easily eroded. He also points out that the mountain is so surrounded with glaciers, that the débris is carried away as soon as formed. This is probably true; but if the peak, as Giordano considers, is composed of regularly bedded rocks rising gently towards Monte Rosa, the peaked form could scarcely be developed unless other intersecting structural lines existed in the mass. (See section of the Matterhorn in Whymper's 'Scrambles among the Alps in 1860–69,' 2nd edit., p. 425).

M. Desor points out that the sedimentary formations of the Alps seldom rise as high as the crystalline rocks. Each central crystalline mass presents a long or ellipsoidal nucleus, the highest point being on the whole coincident with the middle of the mass. From this it follows that the depressions in the Alpine chain correspond with the intervening spaces between the ellipsoidal masses. Here, accordingly, are found the accessible ridges, the St. Gothard and the Simplon being almost the only Passes in Switzerland that do not follow the zones or depressions of the crystalline rocks.

morphosed. So far as we know, the Archæan strata were both thrown in great folds and plicated in detail, were universally subjected to a metamorphism such as in later rocks seems to have been accomplished only at a depth below the surface, and were subsequently worn away upon a most stupendous scale before they received any sedimentary covering within the regions now accessible for examination. Compared with this all other chronological breaks are trivial, and we may almost say that, compared with this, all other stratigraphical breaks are local" *.

A Consideration of the Forces to which the Archæan Series have been subjected.

The evidence that the Archæan rocks the world over have been buried under immense bodies of sediment, of which they may have formed the lower series before the deposition of the Palæozoics upon them, seems to be irresistible. Those who have most studied them in their perplexing relations, if agreed upon nothing else, seem satisfied that this has been the case. It is shown by the various writers quoted that they have been subjected to an enormous amount of compression in pre-Cambrian times which has assisted to produce the special gneissic, schistose, and crystalline characters they assume. It is immaterial to the immediate object of this chapter whether the foliation-planes are planes of bedding or planes of pressure, whether there is an older and a newer gneissic series, as many observers seem to think who have independently studied the rocks in different countries thousands of miles apart, or whether the divisions adopted by Archæan geologists in this country are based upon sound principles of geology. Whether the bandings represent bedding, foliation, or fluxion structure, they equally are evidences of great lateral strains and internal compression.

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* 'Nature,' Jan. 18, 1883, p. 261.

We will, however, for the moment neglect the previous geological history of these mysterious and interesting rocks, accepting them as crystalline gneisses and schists underlying the sedimentary beds, that subsequently, through a long course of geological time, were deposited upon them in those portions of the earth where they now form axial cores of great mountain-ranges.

We have seen by the fullest and most important evidence—the evidence of almost every geologist of eminence in every part of the world where the subject has been studied—that the greatest disturbances of the strata, both Archæan and post-Archæan, are found where the sedimentaries are the thickest.

Accepting the pre-Cambrian crystalline character of the Archæan rocks, let us consider what would be the effect on the rocks of the cubical expansion which we have seen takes place on the rising of the isogeotherms where great bodies of sediment have been thrown down. Lest it should be thought that I am unconsciously exaggerating the amount of heat brought to play upon the rocks, through tenderness to a theory, let us see what Dana, Le Conte, or Judd put it at, and work from that basis. Prof. Judd considers that at 40,000 feet "we may infer the existence of a temperature capable of producing a decided red heat" *.

Prof. J. Le Conte says, "A line of off-shore sediments many thousand feet thick, thus formed, would cause a rise of the subjacent isogeotherms and aqueo-igneous softening both of the sediments and of the original crust on which the sediments were laid down"†. Prof. J. D. Dana, after stating that with 40,000 feet of sedimentary accumulations the isothermal plane would be raised 40,000 feet, says "under such an accession of heat the bottom of the trough would be

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* 'Contributions to the Study of Volcanoes,' p. 136 of Reprint.

† "Structure and Origin of Mountains," Am. Journ. of Science, April 1878, p. 111.

greatly weakened if not partly melted off. If the lower surface of the crust had dipped down this much into the plastic layer that was beneath it, it would have been actually melted off" *.

We have seen that not only were these mountain-making sediments of great thickness, but they were also widespread. For simplicity I take an area 1000 miles × 250 miles and 20 miles deep raised 1000° Fahr.

We have previously found that the cubic expansion of an equivalent mass (500 × 500 × 20) would equal 52,135 cubic miles—that is, the expansion would equal that excess of material added to the mass (see p. 115).

This mass we will assume represents part of the pre-Cambrian crust of the Earth overlain by 40,000 feet of post-Archæan sediment. That these figures are not excessive may be well seen when we consider that the Appalachian Chain itself extends from Vermont to Alabama, being more than 1000 miles long by 50 to 150 miles broad †. (See Map, Plate VIII. p. 41.) This elevated portion is geologically conterminous with undisturbed beds of the same age extending far to the westward. That they have formerly extended also to the eastward I have already suggested, and I hope to further make it quite plain.

A district 1000 × 250 miles, or 250,000 sq. miles, which would equal our hypothetical area, is a moderate computation of the area of the raised isogeothermal plane ‡. It is necessarily very difficult to ascertain the thickness of a given group of Archæan rocks. Mr. Clarence King estimates that 60,000 feet have been recognized in two great groups separated from each other by a period of disturbance, and that they represent stratified rocks in a

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* 'Manual of Geology,' 2nd edition, p. 749.

† Lyell, 'Travels in North America,' vol. i. p. 94.

‡ As I have pointed out, p. 33, the Carboniferous rocks of the United States east of the Rockies occupy now about 400,000 square miles.

most extreme state of compression. He considers that as uncompacted sediment they must have been originally 120,000 feet thick *.

Without actually adopting these figures, we may reasonably assume that a large portion of the upper part of our block 20 miles thick would be composed of Archæan crystalline rocks, the remainder may be granite or its analogues. Now it is evident that these rocks will not undergo much further compression; therefore our effective expansion may at all events be put down at 50,000 cubic miles (see p. 115). How will this excess be disposed of?

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* "Systematic Geology," p. 729.

CHAPTER XIV.

MECHANICAL EFFECTS OF THE EXPANSION OF A MASS OF ARCHÆAN AND GRANITE ROCKS OVERLAID BY A GREAT THICKNESS OF SEDIMENT.

THE horizontal linear expansion of a mass of rock 250 × 1000 miles, raised 1000° Fahr. in temperature—using my coefficient of expansion, viz. 2·75 feet per mile per 100° Fahr.—would be transversely 6875 feet, and longitudinally 27,500 feet.

Leaving out of account for the moment the effect of cubical expansion, in what form would the enormous lateral pressure developed tend to pack a sheet of rock of this extent and proportion?

Here it is that my experiments with the heating of sheets of lead will help us. Considered as a sheet it would rise up along the heated axis. The strains developed by the pressure acting along the heated axis, assuming it to be longitudinal, would tend to be converted into a transverse movement assisting the elevation of the axial ridge or ridges. It would in addition produce an undulation of the strata between the extreme ends. The compression of the transverse and longitudinal undulations would, if the force were regularly and equably applied, produce a series of anticlinal folds having their longer axes parallel with the longer axis of the sheet of rock, but rising and falling in undulating ridges. It is not easy mentally to follow this movement, and it was on this account principally that I initiated the experiments detailed in Chap. IV. The horizontal pressure, according to this theory, comes inwards from all points of the compass as it does in the heated sheet of lead, and the result will be much the same in Nature as in the laboratory experiment.

Anticlinal ridges are not—as one might incorrectly suppose if only studied in books—indefinitely extended. They curve and die into the surrounding strata quaquaversally, being in fact, more correctly speaking, elongated ellipsoidal domes.

This can be well seen in any country where anticlinal folds on a small scale can be examined, but I shall treat of this more fully further on.

If we conceive the assumed area for its full thickness of overlying sedimentaries to be composed of a number of these sheets of rock, they will, on expanding, move upon each other, packing together in folds. These folded rocks, except where fractured at the surface, will be throughout at every point in contact with each other, the superincumbent pressure being sufficient to prevent the possibility of cavities being formed at any stage of the movement. It is evident from this that they will become thickened at one place, and extended at another. They will in fact, repack themselves by "flowing"*. The form that the compressed rocks must finally assume will largely depend upon the lines of weakness in the strata. It is conceivable in the case of a rectangular block such as we are

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* It is very remarkable how the effect of such expansion is misapprehended; even Prof. Green, in his excellent 'Physical Geology' (3rd edition, p. 670), says of the theory of Scrope and Babbage, "The resistance to expansion will be less in a vertical than in a horizontal direction, and hence the area will bulge up and cause elevation of the rocks resting upon it.

"*It is evident that this explanation accounts only for vertical elevation, and makes no provision for contortion or any form of compression*; in fact the elevation produced by it would be bosses, the strata of which would be arranged in concentric domes which, as we have pointed out, is a structure found in no mountain-chain yet examined."

My experiments, I venture to think, prove to demonstration that this is considering, that if the expansion were pretty equable, slow, and regular, the sheets or beds, if comparatively thin, would arrange themselves in a great number of regular corrugations.

If, however, the rocks gave way in a few anticlinals and synclinals near the axis of greatest temperature, the surplus material would probably flow from below towards the anticlinals and distend them. We must not lose sight of the fact that the lower part of the rocks of the hypothetical block would be really plastic with heat, the overlying lower sedimentary beds being partially softened but still comparatively rigid. The expansion of the rigid top-beds would produce an anticlinal and synclinal arrangement of the strata, while the expanding softer underlying rocks would, from the pressure they were undergoing by increase of volume, be striving to escape along the lines of greatest weakness. The lines of weakness are necessarily the most folded portions of the anticlinals. Into these the partially softened masses below would flow, distending them upwards. Accordingly, as the upper strata, subject to lateral pressure, gave way on one side or the other, the expanding anticlinals would be thrown in that direction. The softened gneiss would flow into and obtrude them in tongues, such as are to be seen figured in many sections of contorted regions. (See Plate XIV. fig. 1, p. 98, and Plate XXIII. figs. 3 & 4, p. 173.)

Manufacture of Lead-Pipes as an Illustration of Flowing.

A consideration of the way in which lead pipes are "squirted" will enable us to understand this process of

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a fallacious view of what would take place. Prof. Green has had in mind, like Sir Charles Lyell, vertical expansion alone and distension of the strata above. A fluid imprisoned in the Earth's crust, and distended by heat, would produce such a "boil or eruption" if the overlying solid rocks were not heated. The expansion of a solid, as I have shown, produces the most intense form of compression.

"flowing" better. A vertical cylinder, in which the piston of an hydraulic press works, is surrounded by a fire to keep it hot. In the top is the die and core of the size of the pipe required. The piston is drawn to the bottom of the cylinder. It is then charged with about 3 cwt. of molten lead. When this assumes a sufficiently "pasty" consistency, the press is set to work, the piston forcing the lead through the aperture of the die in the form of a pipe, which hardens as it becomes exposed. The pipe, as it is protruded through the die, is caught up and wound round a drum until the charge of lead is all forced through. If the pipe weigh 9 lbs. to the yard, the result will be about 36 yards of pipe.

Application of the Illustration.

Let us apply this illustration. The expanding softened mass of rock underlying the less-softened rocks, which are again overlaid by hardened sedimentaries, say 10 miles in thickness, is the *lead*; the surrounding less-heated parts of the crust of the globe, the containing *cylinder*; the expansion of the contained softened mass, the *ram*; the approaching sides of the synclinals, in the rigid sedimentaries, the *die*.

It seems to me quite impossible to account for the extraordinary protrusions of gneissic rocks, such as those figured in the section of the Central Alps, except on the hypothesis of their flowing somewhat in the manner described *.

To simplify the problem, I have taken for an example a rectangular block. In nature, of course, the heated mass never has rectangular boundaries. It more nearly approaches a lenticular form.

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* The above was written before I had the opportunity of consulting Daubrée's masterly researches in Experimental Geology. I was pleased to find that his explanation of the fan-structure of the central gneiss of Mont Blanc is almost identical in fact, if not in terms, with the above (see 'Géologie Expérimentale, pp. 435–437).

Let us now assume a lenticular mass, measuring 1000 × 500 miles, and 20 miles deep in its thickest part, raised to a mean of 1000° Fahr. above its previous temperature, and having the same volume as before. How would this alteration of form modify our problem? The effect would be that the horizontal expansion would proportionately increase, while the cubical expansion would remain the same. The upper and more rigid strata would expand double the extent in one direction, so that if the same number of anticlinals were formed as before, they would from this cause be twice as large.

But it will probably be said that this expansion is insufficient to account for the lengthening of the strata such as is found in great mountain-chains. A. Heim estimates that the strata of the Alps measure 72 miles more over the convolutions than across the base. Le Conte says in the Coast Range of California from 15 to 18 miles of sea-bottom has been compressed into 6 miles; and many geologists are of opinion that the strata on each side of a mountain-range have advanced towards each other to the extent of the difference between the length of the folded rocks and the length of the base-line. This is on the assumption that the ranges are due to a collapsing crust gravitating towards a shrinking nucleus. Notwithstanding the support this theory has received, we find on examination that there are good reasons to believe that the cooling of the earth has not advanced sufficiently to produce such effects. The amount of contraction of the globe required to build mountains in this way is something incredible, and, according to the views here set forth, cannot have taken place.

It is also barely conceivable that two places on the Earth's surface should advance towards each other a distance of, say 60 miles, and the movement of the land or crust, supposing it the result of secular contraction affecting the whole earth, be confined within the limits of a mountain-chain even

1000 miles long. According to the theory I have attempted to develop in this work, the *surface*-strata of the flanking ground of a mountain-range do not advance towards anticlinal and synclinal flexures. It is only the underlying beds and deeply-buried rocks expanded by heat, or extended by the struggling expanding masses below, that are lengthened. The base-line of the mountains remains ever the same length.

If we accept the foregoing explanation, the lengthening of the strata takes place deep down in the bowels of the Earth, in beds that only become exposed by long continued denudation. The sheets of rock overlying the plastic mass are corrugated first by their own expansion. In some cases the lengthening may have stopped there, but in highly contorted districts, such as the Alps, the Highlands of Scotland, and the Appalachians, the strata have been further distended by detrusion from below.

It is necessary to clearly realise the fact that either thickening or lengthening of strata may take place without fracture at a certain depth below the surface. The superincumbent pressure being so much in excess of the crushing weight will compel the strata to flow without rupture.

How is it possible to explain loop-like folds (such as are figured in Plate XXIII. fig. 4, p. 173) by lateral pressure alone? Are they not rather the effect of distension and flow in the direction of least resistance?

The dimensions of the hypothetical area I have taken as an example are, I believe, much exceeded by many of the mountain-making areas of sedimentation. Is it not evident from the examples given of Mesozoic strata caught and preserved in the compressed synclinals of gneiss in the Appalachians that the gneiss was formerly covered by these newer sediments? As previously stated, there are good grounds for believing that these sediments formerly covered the gneiss of the Atlantic slopes of the Appalachians, and that they have been removed by denudation.

If, as most observers believe, these crystalline rocks were once ordinary sediments, it is not difficult to understand how the bedded and schistose character of the exterior of the masses changes into a granitoid structure towards the heart as, in the Rocky Mountains, the two rocks are, according to Mr. Clarence King, of identical composition *.

Pre-Palæozoic Surface.

In considering the problem as stated in the preceding pages, I have assumed the pre-Palæozoic surface of the gneissic rocks to have been a plain. It may, however, have been undulating or even mountainous.

The geologists of the 40th parallel seem to agree in the opinion that some of the cores of the ranges were old Archæan mountains, much denuded, which have been again compressed and elevated by the forces which plicated the overlying Palæozoic sediments.

Examples of twisting and recontortion of these "island masses," as they are called, have been given.

This is not inconsistent with the theory of mountain-building here enunciated; on the contrary, it gives a further insight into the plasticity of crystalline rocks under enormous pressure.

Crushing of Gneissic Rocks and Granite.

But the expansive force does not always expend itself in folding and flowing. In some cases a crushing of the rock itself takes place, and an after-reuniting of its constituent grains. Prof. Bonney, who has devoted much time to this phenomenon, describes several specimens of crushed gneiss from the Highlands, collected by Dr. Callaway; some of these have a puzzling resemblance to clastic rocks †.

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* "Systematic Geology."

† "On a series of Rocks from the North-west Highlands," Q. J. G. S. August 1883, p. 417.

Again, he says of the Alps, specimens of schists may be obtained "in which the layers have evidently been crumpled up after the period of mineral change: the bands of quartz and felspar have been as it were crushed together, the flakes of mica are sometimes crumbled and sometimes twisted round into a new position."* "The older Alpine rocks frequently testify to having undergone an extraordinary amount of crushing. In the middle of coarse gneisses, for example, streaks and thin bands of mica-schist may be found, which are not due to an original difference of materials, but to the fact that here and there the original rock has yielded to an enormous pressure, and has been crushed *in situ* into lenticular bands of rock-dust, from which some new mineral developments have taken place."

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* 'Building of the Alps.

CHAPTER XV.

ENORMOUS FORCE DEVELOPED BY EXPANSION AND ITS POSSIBLE EFFECT.

HITHERTO we have only considered the *amount* of expansion caused by a given rise of temperature in a mass of rock of given dimensions, and have assumed that the force developed will be powerful enough to cause all the phenomena of folding and crushing, such as we learn from the testimony of eminent geologists has taken place in the body of mountain-ranges. Perhaps to any one practically acquainted with the terrific force generated through expansion by heat, it would not be necessary to do more. It will, however, serve to give more completeness to our ideas if we stop to consider how such a force will compare in intensity with other forces usually invoked in theories of mountain-building. The rule for estimating the force exerted by an expanding bar, is that it is equivalent to the mechanical force necessary to extend or compress the bar through the same distance that it has expanded. One ton per square inch of section will compress wrought iron $\frac{1}{10,000}$ and steel $\frac{1}{15,000}$ part of its length. A rise of 14° Fahr. would expand wrought iron to the extent of $\frac{1}{10,000}$, and about 11° to 12° Fahr. will expand steel to the extent of $\frac{1}{15,000}$ of its own length. Therefore 14° Fahr. in wrought iron, or 12° Fahr. in steel, will develop a force of 1 ton per square inch.

What the compressibility of rock within elastic limits is I have no experiments to show. It is seen, however, that the force developed bears a relation to the compressibility. Now rock at 10 miles deep will be powerfully compressed. To compress it further will no doubt require a proportionately greater force at such a depth.

The force exerted by a given rise of temperature will therefore be greater in the rocks under such a great superincumbent weight than at the surface; probably a force of 100 tons per square inch will be developed in rock at this depth with a rise of 1000°.*

Let us see what such a pressure would be capable of effecting.

Transfusion by Pressure.—Mr. Walthere Spring subjected filings of different metals to the enormous pressure of 7500 atmospheres or about 50 tons to the square inch. The result was the production of a solid block, which, instead of consisting of grains of the different metals merely adhering, became a true alloy. When a mixture of filings of bismuth, tin, and cadmium, in the proportion to form "Wood's Alloy," was compressed, a solid metallic mass was obtained having properties different from either those of bismuth, or cadmium, or tin. It melted in water of the temperature of 113° F., 99° below the boiling-point, or that which the hand can just bear. Bismuth melts at about 512° F., Cadmium at 442° F., and Tin at 451° F. The mean of them is 468°. The alloy therefore is a true compound.†

Prof. Roberts-Austen gives the following table of the results obtained by Mr. W. Spring by the compression of finely divided metals :—

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* The Rev. O. Fisher calculates that the horizontal force of compression thrown into a stratum at the Earth's surface by the shrinking away of the underlying parts, would be equal to the weight of a piece of the same stratum of the same section as the stratum and *two thousand* miles long =830,200 tons per square foot ('Crust of the Earth,' p. 36). Without disputing the theoretical accuracy of this calculation, it will be safe to assume that the practical conditions for the effective exertion of such a pressure never occur in nature.

† Science Notes by Mattieu Williams, 'Gentleman's Magazine,' February 1883, pp. 231-2.

Lead	*welds*	at a	pressure of	13	tons	per square inch.
Zinc	,,	,,	,,	19	,,	,,
Tin	,,	,,	,,	32	,,	,,
Antimony	,,	,,	,,	38	,,	,,
Aluminum	,,	,,	,,	38	,,	,,
Bismuth	,,	,,	,,	38	,,	,,
Copper	,,	,,	,,	38	,,	,,
Lead	*flows*	,,	,,	33	,,	,,
Tin	,,	,,	,,	47	,,	,,

When more pressure than 50 tons to the inch is applied, the metals submitted to the action of the machine begin to flow through the fine cracks of the compressing chamber "just as if they were so much treacle. Mr. Spring has proved that it is possible to press powdered crystalline metals into masses of another crystalline structure, just the same as by fusion." *

Mechanical Effects of Punching.

We may, by considering the effect on iron of punching, obtain an insight into the behaviour of metals under pressure, and, by inference, into that of rocks. 'The Engineer,' in an article October 22, 1880, p. 301, says :—" Punching is but detrusion or changing the position of the particles of a solid, and time seems to be the only limit to the amount of this change of position producible by a given force. Even the most rigid and brittle bodies change their form without breach of continuity, if sufficient time be given for the action of the detrusive force, as is evidenced by the distorted changes of form produced in strong univalve sea-shells found imbedded in laminated rock. Thus a punch of $\frac{7}{16}$ in. diameter was forced through a rectangular block of iron $1\frac{3}{16}$ in. thick. In piercing such a block the punch traverses about half the thickness of the block before any punching or core makes its appearance. From experiments made upon the relative specific gravities of the iron of the block, and that of the core forced out of it, it is concluded that during the earlier part of the penetration the metal displaced is forced to *flow out* laterally round the deeper part of the block, and that the remaining portion of compressed metal or core is not forced out until the circumferential resistance of the metal of the block or nut to further outflow equals or exceeds the resistance to shearing of the core from the metal around it."

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* "Properties of Fluids and Solid Metals." Lecture at the Royal Institution. Report in 'The Engineer,' April 9, 1886, p. 278.

The Flow of Solids.

The experiments of M. Tresca show that at ordinary atmospheric temperatures solid bodies, like lead, cast-iron, and ice, may be so compressed as to undergo an internal motion of their parts closely analogous to that of fluids. Thus a solid jet of lead has been produced by placing a piece of the metal in a cavity between the jaws of a powerful compressing machine. Iron, in like manner, has been forced to flow in a solid state into cavities and take their shape. On cutting sections of the metals so compressed, their particles or crystals are found to have ranged themselves in lines of flow which follow the contours of the space into which they have been squeezed*.

In a paper read before the Institute of Mechanical Engineers, at Paris, and reported in the 'Engineer,' June 7th, 1867, M. Tresca showed, by a very beautiful series of experiments, that if lead or any other metal were placed in a series of disks in a cylinder having a hole at the bottom, and were then compressed, the metal would flow through the orifice in a series of concentric tubes. The disks out of the influence of the flow remain flat, while in the part constituting the jet the individual layers converge to form the jet; before passing through the orifice, all the layers bend over so as to enter into the jet simultaneously, as though they individually followed a general current directed towards the orifice. The external surface of the jet is entirely composed of a cylindrical envelope, formed out of the bottom disk of the original mass. Each of these tubes is closed at the outer extremity by a cap more or less convex, which is the central part of each of the original disks. With two circular orifices of exactly the same diameter drilled in the die, and placed symmetrically with regard to the axis of the block, the result was not two equal tubes but one larger than the other; and on taking the block out of the die, it was seen that the general motion was directed from all points of the upper portion of the block towards the orifice which produced the larger jet. Experiments were also made on the flow of solids through lateral orifices, from which Tresca draws the following conclusions:—

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* Geikie, 'Text-book of Geology,' 1st ed. p. 313

"That where pressure is exerted upon the surface of any material it is transmitted in the interior of the mass from particle to particle, and tends to produce a flow in the direction where the resistance is least.

"The transmission of pressure is unequally distributed, as the particles situated at the orifice do not participate in the flow to the same extent; and there are even points where the loss of pressure is carried so far as to become *nil.*"

Experiments were also made with lead disks enclosed in a cylinder, and compressed by a plunger of less diameter. The lead flowed into the annular space, assuming the form of a tumbler.

The uppermost plate was developed almost in one piece to the upper edge of the tumbler*.

M. Tresca says, "For all bodies two distinct periods are recognized—the period of perfect elasticity, which corresponds to variations of length proportional to the pressures applied; and the period of imperfect elasticity, during which the changes of dimensions, on the contrary, increase more rapidly than the pressures"*.

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* 'Engineer,' June 28, 1878, p. 463

The second phase leads finally towards a condition in which a given force sufficiently great would continue to produce deformation without limit, such as may be observed in the process.

This leads to a third period, designated by M. Tresca as the period of fluidity, to which the greater part of his experiments are related.

M. de Saint Venant has given the name of Plastico-dynamics to the study of pressures transmitted in this way.

Extension of Strata caused by Detrusion.

The thickening or thinning of the strata by the various forces brought into play during the building of mountain-ranges by the expansion of portions of the Earth's crust, is of so much importance to a correct conception of the origin of mountain-structure, that it will be necessary to revert to it again.

If we conceive the heated block we have been investigating, p. 154, to be composed of a series of beds like the disks of lead experimented upon by M. Tresca, and follow their behaviour when subjected to expansion while enclosed in fixed lateral boundaries, we shall find that the following will be the result.

The line of weakness or extension along the upper strata will determine the direction of the flow of the underlying plastic matter as it expands in bulk. Let us assume that the strata rise up in a simple anticlinal, as shown at D, fig. 4, Plate XVII., p. 117. Commencing with the bottom bed, No. 1, and proceeding in the ascending order, we shall find that if the whole of the beds be raised through the same number of degrees of temperature, No. 1 will have a cubical expansion under the anticlinal, which we may represent by 1;

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* 'Engineer,' June 14, 1878, p. 428.

Nos. 1 and 2 combined by 2; Nos. 1, 2, and 3 by 3; and so on until we come to bed 20, at the top, when the cubical expansion of the whole of the block will be represented by 20. That is, the cubical expansion of the mass will be twenty times that of the bottom or any individual bed composing the series. Assuming a sufficient superincumbent weight to keep the mass solid, it is evident that the material of the bottom bed must *flow* in order to ridge up, as seen in the diagram.

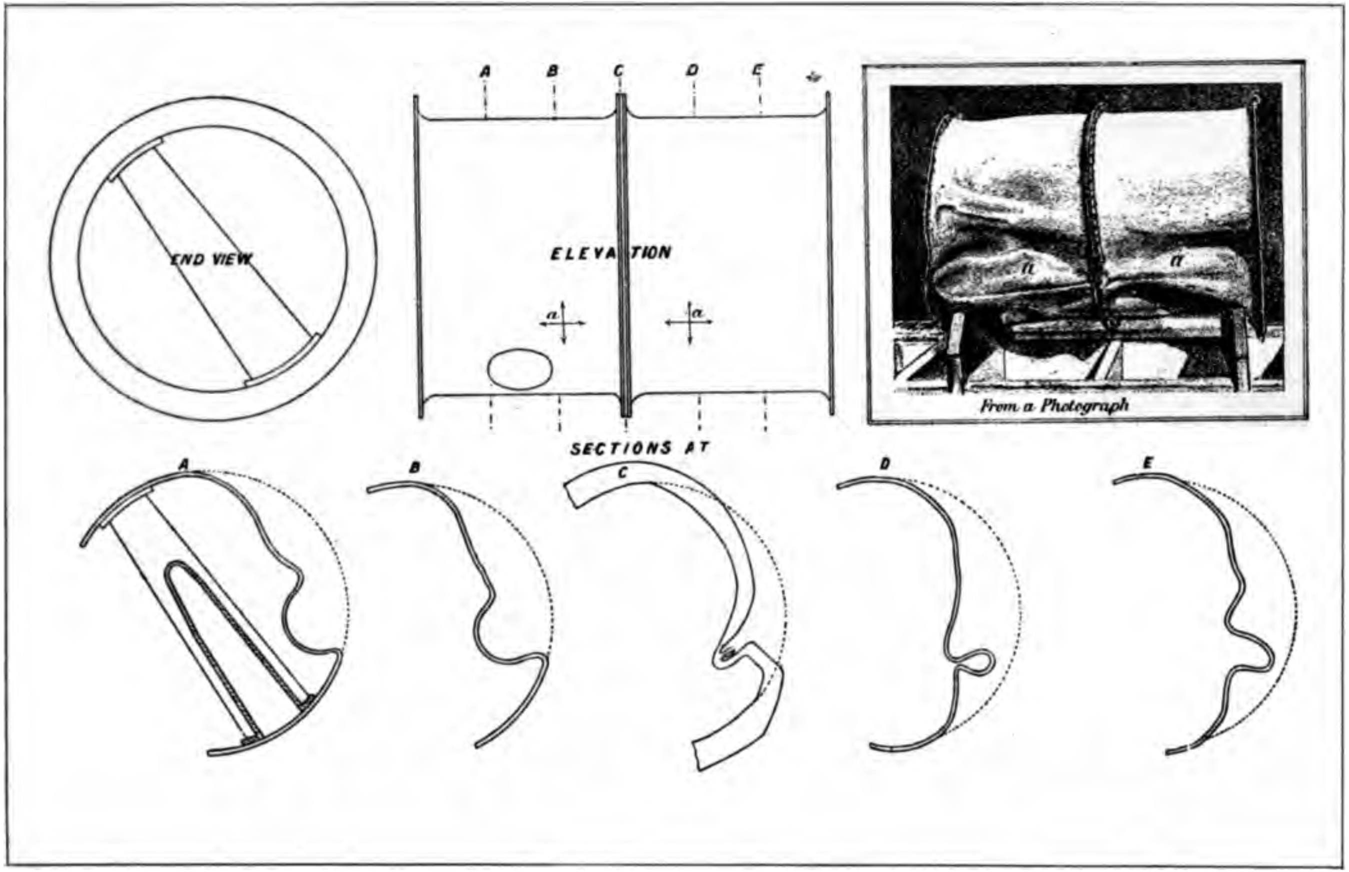
The same with the second, and with the third, and so on. If, therefore, we have a sufficient number of beds in the series, we shall arrive at a point *e* at which the linear expansion will not be sufficient to enable the beds above to wrap over the anticlinal, and tension of all the beds above this point will result. Nevertheless, assuming the superincumbent weight to be sufficient to make the solid rock flow, a horizontal extension of the beds that are in tension above that due to simple heating will take place.

If, however, as is the case with the strata of the Earth's crust, the lower beds are subjected to a greater temperature than the upper, the latter will be proportionately affected by extension from this cause, which I will call *extension by detrusion*.

This is what I conceive happens in the upheaval of intensely folded mountain-ranges, especially those in which there are intruded tongues or cores of Archæan rocks. In order to further elucidate these views by practical example, a method that brings the ideas more plainly before the mind, I give an illustration, Plate XXII., showing, in a very remarkable manner, how extension may take place by forces that at first sight would appear more likely to crush the material together than to extend it.

Have the geologists who have attempted to measure the original length of the beds in certain folded and compressed areas taken this drawing-out, or rather pressing-out, of the strata into consideration? It would appear not; the beds

Plate XXII.



MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

Sprague & Cº Photo-litho London

PLATE XXII.

Example of Tension caused by a Compressive Force.

This is an illustration taken from the 'Engineer' of February 19th, 1886, representing "perhaps the most remarkable specimen of a collapsed tube anywhere to be found." The tube formed the flue of a boiler, and was built of steel plates; it was an exhibit at the Calcutta Exhibition. "It was formed of flanged rings riveted together, each ring consisting of one plate welded and being flanged to form one piece. These separate rings were then riveted together by their flanges with an expansion-ring between to form the flue, the flanges, together with the Galloway tubes, giving great strength to the whole. Two of the rings, apparently those immediately behind the fire-bridge, were exhibited, the greatest concentration of heat having apparently been at the junction of the two rings, since the depression on both sides of this was about equal. The first parts to yield to the combined influences of heat and gradually increasing external pressure were those marked *a* and *a*. During their depression the flange was being heated, the level of the water lowered. The depressions increased, and thus brought into play the resistance offered by the tensile strength of the metal. These forces (shown by the arrows at *a—a*) increased with the depression, and ultimately were so great, when assisted by the softening of the flange and the external pressure, as to pull it down, and, by thus opening the joint, to disclose the collapse. The amount of this tensile force may be imagined from the fact *that the plate had elongated* 6 *inches in* 33 *inches by bulging downwards*" *.

This very instructive collapse shows us how foldings and extension of strata may be caused by the regular and equable application of a compressive force. In the case of the boiler-flue the compression was from the steam in the boiler acting externally on the flue, which, becoming softened by heat, folded and bulged inwards. The plate of the flue became also *lengthened by expansion* as well as extended by the pressure. The stay shown at A would help to prevent the entire collapse of the flue.

It enables us to understand that once a fold is instituted having an expanding mass of matter in its concavity, be it gas, steam, or solid flowing rock, such matter will, in struggling to escape, extend the fold to a greater size. The application of this example to the Archæan folding explained in this Chapter is obvious.

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* Quotation from Government Report on the Exhibition.

in such estimates are assumed to be of their original thickness and length, which I contend they are not. They may be either thicker and shorter, or thinner and longer. Until we can answer these questions, no estimate of the length of a fold is any index of the original length of the bed before folding. Again, it is assumed that the denuded tops of the anticlinals were once continuous as arches spanning the respective areas. This, again, we have reason to suspect is not in all cases true.

Professor Claypole estimates that 65 miles of a section of the Appalachians along the Meania sandstone represents about 100 miles of surface before corrugation took place. He observes:—"Such mass motion as this involves the displacement of whole countries, and the *shoving of their superficial strata over those below them* * to an extent seldom fully realized. The travelling of a whole country in this manner for thirty or forty miles is a view of geology not easily pictured to the mind; yet the south-east line of Cumberland County must have moved over at least this distance. Towards the north-west this movement diminished until the sliding, yielding mass was arrested against the beds of the Midland district, which formed the great buffer-plate on which the earth-pressure spent itself"†. I give this quotation as embodying the consequences of the Contractional theory in its boldest form.

After an examination of the possible effects of the Earth's contraction in Chapter XI., it is difficult to assent to these views. Taking the extremest estimates, we should find it next to impossible to get sufficient linear contraction to account for such wholesale geographical disturbance‡.

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* The italics are mine.

† "Pennsylvania before and after the Elevation of the Appalachian Mountains." British Assoc. Report, 1884, p. 718.

‡ Prof. Joseph Le Conte, I am pleased to find, fully recognizes the extension the folds have undergone in the Coast-Range of California. Amer. Journ. of Science, 1876, p. 299.

Let us examine this idea a little more in detail. To begin with, it seems evident that a mountain-system like the Appalachians could not be formed until the crust had become of a very considerable thickness.

But the Appalachians were upraised at the close of the Carboniferous age. Before that period stupendous mountain-ranges were in existence, formed out of Silurian and Cambrian sediments. And, again, we are informed, on the best authority already quoted, that great mountains, built out of the still older Archæan rocks, preceded the deposition of the Palæozoic sediments.

Every one of these separate operations demands a strong and rigid crust to work upon*.

If, then, we even accept Mallet's estimate, that the Earth, since it was all a molten mass, has shrunk 189 miles in its diameter, we must admit that the greater part of this shrinkage occurred before Archæan time. The amount of shrinkage of the Earth is variously calculated according to the physical point of view from which the mathematician looks at the problem. We have seen that Mr. Osmond Fisher calculates that its total amount is only 1·9 mile.

If we allow a contraction of 40 miles † for the Appalachians alone, we shall have to add something for the Carboniferous ranges in the Western Territories—for the Pennine chain in England, the Carboniferous mountains of Belgium, the Ural mountains in Russia, and many more of the same age on various parts of the Earth's surface.

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* Prof. Jas. Hall says, "Even long prior to the deposition of the Potsdam Sandstone the forces which had disturbed the pre-existing continent had ceased, and, in contradiction to the generally entertained opinion that in more ancient times there was more disturbance of the crust, there has scarcely ever been, since the advent of life upon our globe, so wide an area or so long a period indicating repose of all the disturbing forces."—Address to Amer. Assoc. for the Advancement of Science, 1857, p. 9.

† Estimated by Prof. Claypole at 40 miles crumpling.—Prestwich's Geology, Chemical and Physical, p. 250.

Plate XXIII.

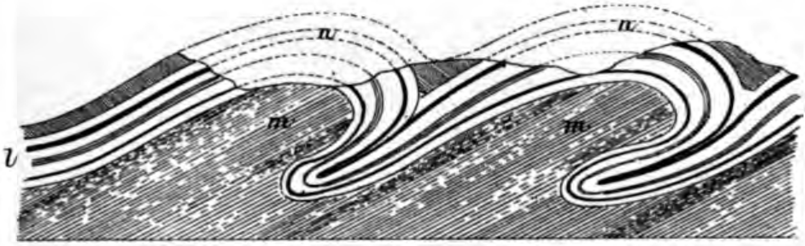

Fig 4

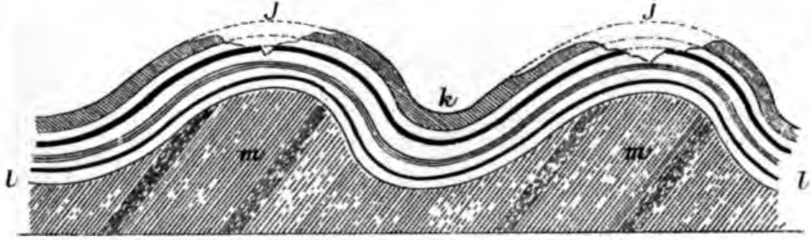

Fig 3.

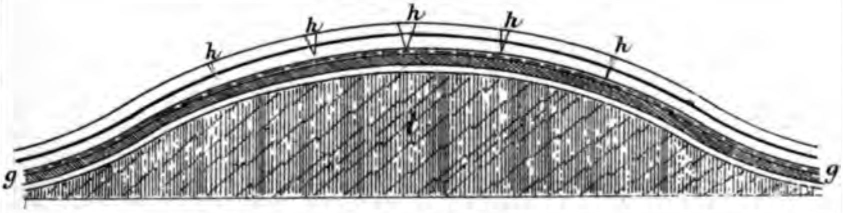

Fig 2.

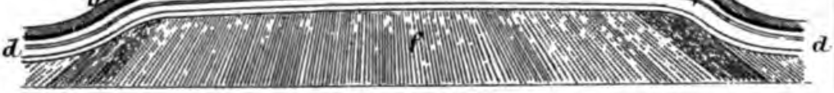

Fig 1.

MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

Spragu[illegible] London

PLATE XXIII.

Diagrammatic Illustrations of several types of Monoclinal and Anticlinal Flexures having Gneissic, Schistose, or Granitoid Cores.

Fig. 1. Represents in section an uplift-plateau, *a*, slightly arched, bounded by monoclinals, *b* and *c*. The sedimentary strata, *d*, have been lengthened in their lower beds by expansion, but ruptured at *e e* by tension. Type of the Colorado plateau system, which is one expression of the cubical expansion of the deep-seated crystalline rocks shown at *f*.

Fig. 2. Section of an anticlinal dome. The sedimentary strata, *g*, have been lengthened in their lower beds by expansion, and ruptured, at *h h*, by tension. *i* is the crystalline core, protruded by cubical expansion. Type of the Black Hills of Dakota.

Fig. 3. Transverse section of two anticlinals, *j j*, with synclinal, *k*; unsymmetrical, having the steepest dip to the right. The sedimentaries, *l*, lengthened in the lower beds by expansion, have been further extended by compressive extension (see Plate XXII. p. 169) due to the detrusive action of the flowing crystalline cores, *m m*. The apices of the anticlinals, *j j*, have been fractured and denuded.

Fig. 4. Further development of the anticlinals shown in fig. 3. By the protrusion of the tongues of crystalline rocks, *m m*, brought about by cubical expansion and horizontal pressure, the anticlinals are thrown over to the right in wave-like form, and the sides of the synclinals are closely compressed together. The sedimentary strata, *l l*, are lengthened in the synclinals by pressure, and in the anticlinals by the detrusive action of the crystalline tongues, *m m*. The crowns of the anticlinals, *n n*, have been removed by denudation. Type of some of the folds of the Central Alps and of the Appalachians (see Plate XIV. fig. 1, p. 98, and Plate IX., p. 42).

Therefore, if we consider the sediments overlying the preexisting crust, which may have been granite or Archæan gneiss and schist, or those rocks overlain by early Palæozoics on which subterranean forces have been expended in a previous period of the Earth's history, to be divided into twenty beds, as in the preceding example shown in Plate XVII. fig. 4, p. 117, the lower bed of the newer sediments will be affected by, and have to conform to, the movements and flow of the deeper-seated rocks.

In adapting itself to these movements it will be assisted by its own longitudinal expansion, which of itself would produce anticlinal and synclinal folds.

The anticlinals will be lines of weakness, determining to some extent the flow of the underlying rocky matter.

The underlying rocks, acting under great compression produced by the expansive agencies already described, will tend to thin out the arch into which they flow, and extend it beyond the length of the expansion due to the rise of temperature it has undergone.

The cores of mountain-ranges so frequently prove to consist of crystalline rocks that we cannot, with any approach to truth, always attribute them to pre-existing mountains. In many mountain-ranges we cannot see the foundation rock on which they rest; doubtless, could we do this, we should observe the same phenomenon of crystalline rocks in a modified form.

If the plastic rock-strata—plastic by pressure—be forced up in fan-like form, as it was in the Central Alps (see Plate XIV. fig. 1, p. 98), the overlying Palæozoics on the shoulders or flanks of the protruding core will be folded back upon each other and tightly compressed.

This compression will tend to further lengthen their component beds, as the line of least resistance will be upwards, and the beds will flow and lengthen in that direction. By these combined influences the measurement along the fold will be very much greater than along the original base-line.

The tendency of each bed to expand, even as it is being thrown back, will produce a rolling or partial rotation round the axis of the fold.

The compression produced by these opposite forces, the central intrusive gneissic mass and the expanding beds on the flanks of the range, will, after a certain point of flexure is reached, produce a fracture or reversed fault.

The thinning out of the beds by pressure may be well studied in the case of highly plicated coal-strata, such as those in Pembrokeshire figured by Sir Henry De la Beche in the 'Geological Observer' (2nd ed. p. 648); inasmuch as the coal is a softer material than rock, the thinning-out is more exaggerated in the coal-seams than in the rock-beds. Nevertheless, the harder beds partake of the same movements, although it is not always so easy to prove it.

EXAMPLES OF CONTORTIONS IN BEDDED ROCKS.

A well-known example of contorted rocks is that at Draughton, near Skipton. I examined the quarry in July 1882. The quarry-face was then due north and south, showing two anticlinals and an intermediate synclinal.

The strata consist of a series of thin beds of Carboniferous limestones, with intermediate partings of shale.

The strike of these remarkable folds, represented in Plate XXIV. fig. 1, p. 179, from a sketch made at the time, is due east and west. "The folds are parallel to, and, no doubt, form part of, the great anticlinal elevation of Skipton, commencing at Thornton, and passing through Skipton by Blubberhouses to Harrowgate, being in fact one of the most remarkable subterranean ridges on record"[*]. The bedded core of this anticlinal, forming a hog's back with the axis east and west, has been quarried by the Leeds and Liverpool Canal Company on its north side, and is called Haw Bank Quarry. The strata are at a high angle, dipping 55° magnetic north. On the south side of the anticlinal core, on the left of the road from Skipton to Skibeden, is the Skibeden quarry, belonging to Mr. Nicholson, who was not then working it. A remarkable fault is to be seen in this quarry, bearing magnetic east and west. The face of it is curved and tortuous, and well marked with slickenside striations, dipping only 20° from the horizontal in the direction of magnetic east. The strata are much contorted, and the beds recurved against this fault, the strike on the west side being due north and south.

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[*] See Phillips, 'Geology of Yorkshire,' part ii. p. 23; also Ricketts, "On the Carboniferous Limestone near Skipton," Proc. of Liverpool Geol. Soc., Sess. 1879–1880.

Wheetam Rock Quarry, not very far from Draughton, shows a very remarkable synclinal.

The strike of the folds is magnetic east and west, nearly parallel to those at Draughton. The illustration (Plate XXIV. fig. 2), from the sketch I took at the time, shows a quarry-face running magnetic north and south *.

The core of the synclinal at "*a*" was quarried out, and the form of it was like the inside of the bow of a boat, with the keel bearing N.E. to S.W. (nearly), and the "floor" dipping 25° S.W. This was a very excellent illustration of the truth of the statement I have previously made, that anticlinals are in all cases more or less elongated elliptical domes, and synclinal contortions have the same elongated but inverted ellipsoidal form.

There are many more examples of contorted limestone-beds in this neighbourhood. They are very striking, inasmuch as the solid limestone has been bent, without fracture, at an acute angle. The inside of the core at Wheetam was beautifully smooth and perfectly curved.

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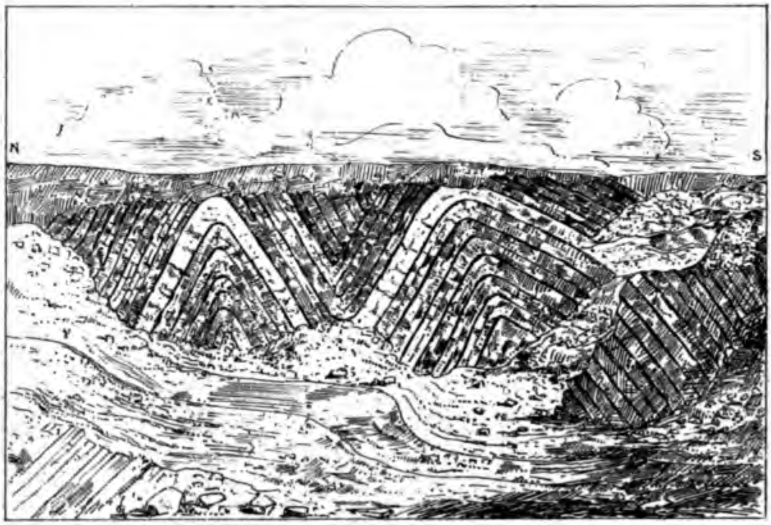
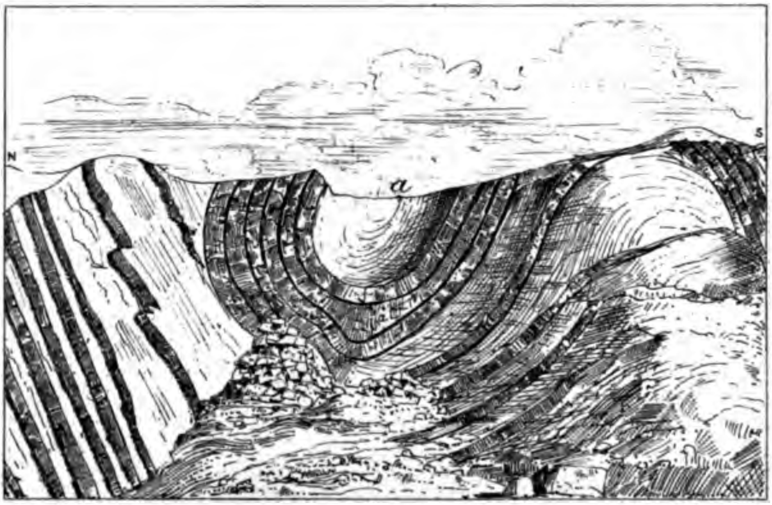
* The magnetic variation is 21° W. at Liverpool.

Plate XXIV.



DRAUGHTON QUARRY (Fig 1)



WHEETAM ROCK QUARRY (Fig 2)

MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.
Sprague & Co Photo-litho London

The Skipton anticlinal is remarkable as crossing the general axis of the Pennine Range at right angles. The form of the subordinate anticlinals and synclinals shows also that though the predominating pressure was from the north and south, there was a pressure also acting from the east and west, or rather, in varied degrees, from all parts of the compass. These contortions are only shown to us through the denudation of an enormous overlying thickness of Millstone Grit and Coal-measures.

In the lead mines at Grassington, fifteen miles from Skipton, the principal faults run east and west, according to Mr. Trevethan, the manager. Here the Millstone Grit is found lying on the Carboniferous Limestone.

In the Scar limestone, which is in massive beds, and therefore cannot be packed into a smaller compass by short folds like the thin limestone-beds already described, are to be seen plate-like laminations, as if produced by pressure from the N.E. and S.W. This I noticed in a quarry on the Giggleswick Road, not far from the Ebbing and Flowing Well, and also in Gordale Scar.

PLATE XXIV.

Fig. 1. Contorted Carboniferous Limestone in Draughton Quarry, near Skipton, Yorkshire (from a sketch in 1882). This is a very excellent example, some of the thicker beds of limestone being, at the apex of the anticlinals, sharply bent without fracture. It was the subject of an excellent photograph published by the West Riding Geological and Polytechnic Society in 1872. (See p. 177.)

Fig. 2. Synclinal in Wheetam-Rock Quarry. The remarkable feature in this example is the form of the core at *a*. At the time the sketch was made the rock was quarried out, as shown. The inside was smoothly modelled like the prow of a boat having "full" lines, or, in other words, was like the concave cast of an ellipsoidal anticlinal. (See p. 178.)

Folded Silurians, Wigtonshire.

Excellent examples of folded rocks may be seen on the Wigtonshire coast. A walk along the shore from Garliestown to Innerwell fishery discloses a series of almost vertical jagged beds, having a general strike N.E. and S.W. and remarkably parallel (see view, Plate XXV. p. 181). It is evident that these beds are closely folded together, consisting of denuded anticlinals and synclinals. In places the crown of an anticlinal is to be seen, in others the interior of a synclinal, their axes bearing N.E. and S.W. They all belong to the Lower Silurian series, and consist of red, purple, and grey grauwackes. The beds vary in thickness from a few inches to several feet.

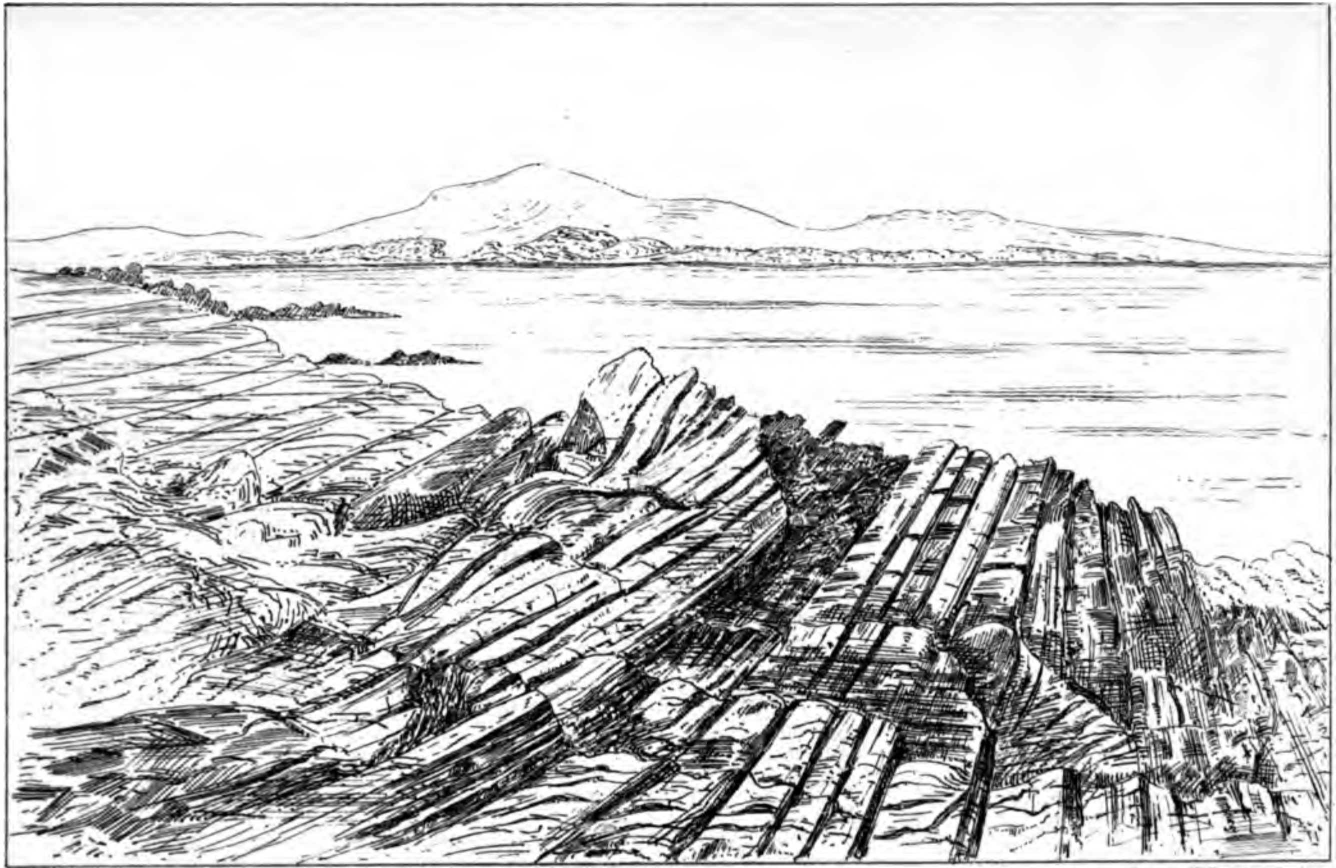
At the isle of Whithorn and adjoining coast still more remarkable examples of contorted rocks of the same series can be observed. They stand out in rugged and jagged cliffs, the geological structure being "skeletonized" by the breakers. The beds are so twisted and folded as in many cases to resemble the timbers of a ship.

The illustrations (Plates XXVI. and XXVII.) are from sketches made in August 1883, and give a better idea of the deformations and distortions the rocks have undergone than a section would. More massive beds may be seen at the Craigs of Garchew, and here also is a good example of a synclinal.

In the cliffs of Kirkmaiden, south of Port William, on Luce Bay, a thin-bedded series of rocks can be seen faulted against the massive beds, resembling those of the Craigs of Garchew. The thin-bedded rocks on one side of the fault have a double curvature, and are more incurved against the fault than the massive beds.

At Ravenshall, in Kirkcudbrightshire, splendid examples of contorted Lower-Silurian rocks can be seen standing out on the shore in serrated ridges.

Plate XXV.

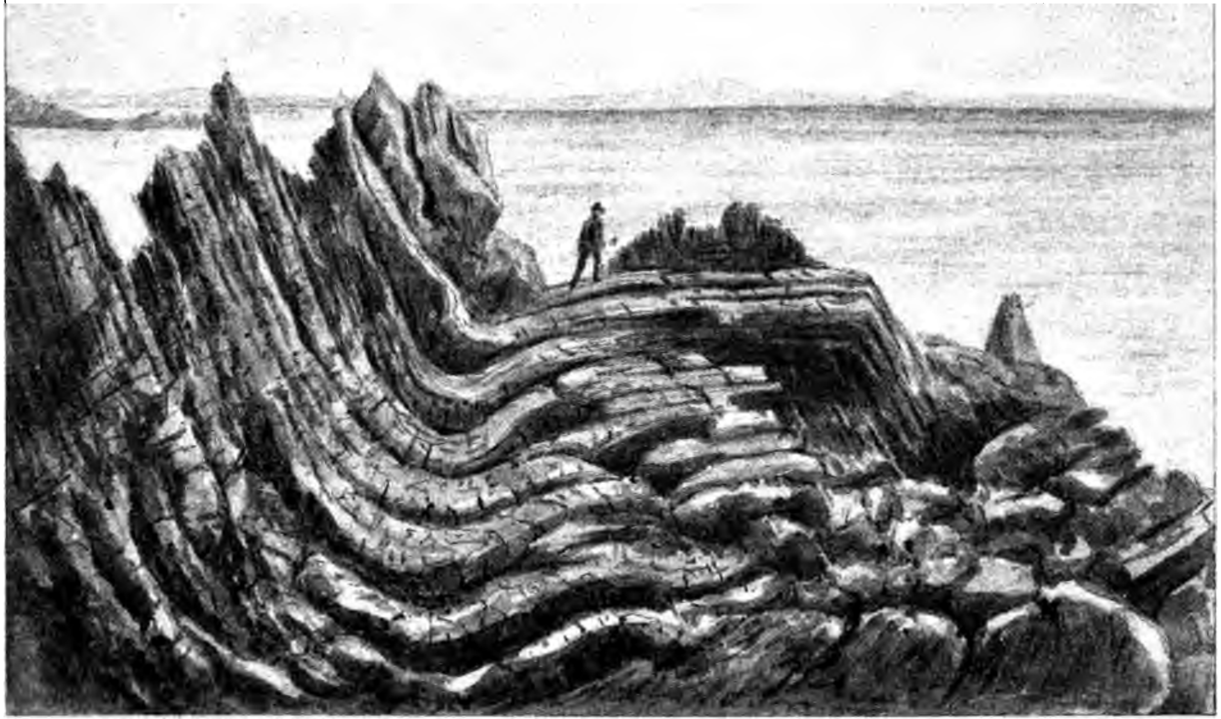


MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

Sprague & Co. Photo-litho London

FOLDED SILURIANS WIGTONSHIRE, N of GARLIESTOWN.

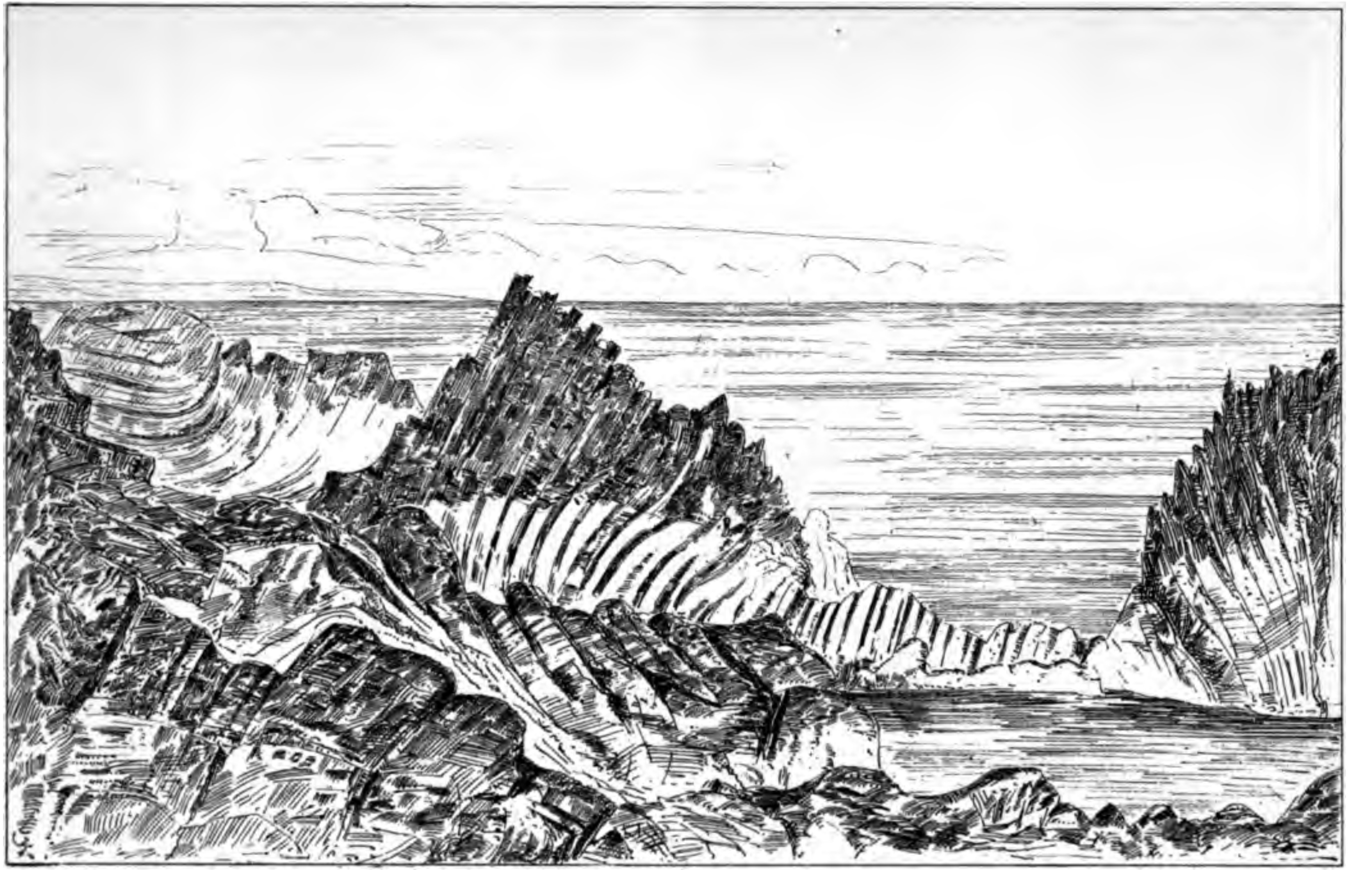
Plate XXVI.



READE'S ORIGIN OF MOUNTAIN RANGES.

INK-PHOTO, SPRAGUE & Cº LONDON

Plate XXVII.



MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

Sprague & Co Photo-litho London

FOLDED SILURIANS . N of the ISLE of WHITHORN, WIGTONSHIRE.

PLATE XXV.

View of Folded Lower Silurian Grauwacke Rocks on the shore near Garliestown, Wigtonshire.

The strike of the beds, which are remarkably parallel, is N.E. and S.W. The distant mountain beyond Wigton Bay is Cairnsmore of Fleet, Kirkcudbrightshire, alluded to on the following page as an immense boss of granite breaking through the Lower Silurians (p. 182). Notwithstanding the pavement-like parallelism of the beds, it has been clearly proved that they consist of anticlinal and synclinal folds. (See p. 180.)

PLATE XXVI.

View of Contorted Lower Silurian Grauwackes in the Isle of Whithorn, Wigtonshire.

These rocks are truly remarkable, the structure being splendidly displayed and anatomized by the denuding action of the waves. The successive beds in their foreshortening look like part of the massive framework of a large ship. (See p. 180.)

PLATE XXVII.

View of Contorted Lower Silurian Grauwackes on the coast of Wigtonshire, north of the Isle of Whithorn.

The dark colour of the rocks above high-water mark is in striking contrast to the white shell-encrusted rocks within the influence of the tide. (See p. 180.)

Through these folded beds of Kirkcudbrightshire an immense boss of granite, forming the mass of Cairnsmore of Fleet, a mountain rising 2612 feet above the sea, and occupying an area of not less than thirty square miles, has burst. I was much interested in discovering what effect this igneous mass had produced upon the surrounding strata.

In Palnure Burn I found a very excellent contact-section, in which specimens showing the granite and the beds in contact could be obtained in one specimen.

The immediate beds were converted into hard schistose rocks, but the metamorphism could not have extended very far into the mass from the exposures of the grauwackes I found in the neighbourhood.

To what extent the beds were displaced by, or absorbed into, the granitic mass I had no means of discovering.

In the explanation of Sheet 4, 'Memoirs of the Geological Survey of Scotland,' it is stated that:—"Round the main granitic centre of Cairnsmore the most intense metamorphism may be seen. As the junction with that rock is approached, the Silurian strata become more and more micaceous, until they pass into true schists near the edge of the mass." The beds immediately round the granite belong to the Ardwell Lower Black Shale and Queensbury groups. "So greatly have they been squeezed and baked, that their bedding is quite obliterated, and the altered rock breaks up into large square blocks. It will be observed also that along the west side of the granite the normal strike of the beds is deflected so as to run almost at right angles to its usual course."*

It is obvious that as this great mass of granite cooled it must still have been subject to lateral pressure from the surrounding strata, and is another example that all shrinkages that occur at great depths are followed either by a lateral extension of the strata, due to the superincumbent weight, or by a bridging over the space by faulting and "keying up," in the way already explained. As the granite must have shrunk in cooling, the fact of its not parting from the surrounding strata shows that in some way a following-up movement of the surrounding Silurian beds must have taken place.

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* P. 18.

Contorted Silurian Strata in Eastern Berwickshire.

In the memoir on "The Geology of Eastern Berwickshire" (Geol. Survey of Gt. Britain, No. 34, Scotland), Dr. Archibald Geikie gives a very excellent description of the contorted and convoluted Lower-Silurian strata of a district rendered classical by the researches of Hutton and Sir James Hall. It was in this region that the latter made his well-known observations on the effects of lateral pressure in folding stratified rocks. Dr. Geikie points out that the range of Silurian hills cut off by the sea between Siccan Point and Burnmouth may be regarded as a vast synclinal trough, with minor anticlinal and synclinal axial lines *. It measures 11 miles across in a bee-line. To the north-west of this belt the prevailing dip is towards the south-east, and represents probably not less than 4000 feet of grits † and shales belonging to the Lower-Silurian series.

It is worthy of remark that, notwithstanding the great compression which these Silurian strata have undergone, anything like defined cleavage is almost unknown; also that the most violent contortions of the strata are not seen in those places where igneous protrusions are most plentiful, but, on the contrary, where such dykes and bosses most abound, there the strata have often been least crumpled ‡.

It was in this district that Hutton made his great discovery of the significance of unconformity. . I must refer my readers to the section in the memoir, showing the convolutions of the Silurian strata, and the relations of the Old Red and Carboniferous strata to the Lower-Silurian series.

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* P. 18.

† Ibid. p. 19.

‡ Ibid. p. 13.

Contorted Lower Silurians at Aberystwyth, Central Wales.

The contorted rocks at Aberystwyth are well worth studying. Having devoted a good deal of attention to the sections exposed on the coast between Llanrhystyd and Borth, a distance of about 15 miles, I propose to illustrate some of the details of folded structure and rock-movements from this district.

From the nature of the folds and the domical convolutions of the rocks, together with the varying angle the coast-line takes with respect to the strike, it would be difficult to find a region in which the secrets of these rock-movements are more clearly divulged.

Strike of the Rocks and Trend of the Coast-line.

The trend of the coast-line is about 10° E. of north. The strike of the strata varies from due north and south to from 10° to 20° W. of north, so that there is a mean angle of about 25° between the coast-line and the strike-line.

This relation of coast-trend and rock-strike, in directing the denuding forces, has been very favourable to developing the structural anatomy of the region.

The denudation, caused principally by the wave-action, and determined by the strike and varying angles of dip as the succession of anticlinals and synclinals are cut through, has serrated the coast into small bays and headlands, and further disclosed its structure in sections at various angles to the strike.

The series of rocks have been named the Aberystwyth Grits *. They consist of a succession of siliceous grits of concretionary origin, with interbedded shales. In some cases the nature of the beds approaches that of clay-slate, but nowhere do the beds possess a really defined cleavage. The underside of the grits is distinguished by very singular protuberances of concretionary origin, having, over considerable areas, a remarkable parallelism of direction. As pointed out by Mr. Walter Keeping, the underside of the grit-beds can be distinguished by these tear-like drops even when reversed, which occurs sometimes inland.

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* "The Geology of Central Wales," by Walter Keeping, Quart. Journ. Geol. Soc. vol. xxxvii. p. 144, 1881.

It is evident that the dip of the beds on the coast will be either east or west, accordingly as the anticlinals and synclinals are intersected west or east of their axes. When they dip east the rocks stand out as bold promontories like Craiglas, north of Aberystwyth; but if the bedding be carefully followed eastward, it will be seen to curve upwards again, so that the beds show their flanks in a nearly vertical wall facing the sea. This is really the interior of a synclinal.

Domed Form of Anticlinals.

At the north end of Clarach Bay the elongated domical form typical of anticlinals can be well seen. The flanks of the dome are exposed, and the edges of the strata that successively wrap round it are seen while proceeding from north to south. The backs of the convex beds are very smooth and true, and in many cases marked with slickenside striæ. In one set of beds I found the direction of the striæ was S.W by W., following the convexity of the surface (Plate XXVIII. fig. 3, *a–b*, p. 187). I took specimens of both the upper surface of the underlying and the under surface of the overlying beds, and found both marked with fine striations. It is still more remarkable that a little north of these striations, about 12 feet lower down in the series, I found striations on the convex back of the anticlinal, having a direction N.W. by W. (Plate XXVIII. fig. 3, *c–d*).

It is evident from these facts that the beds, separated vertically only 12 feet, have moved or rolled over each other at a horizontal angle of from 50° to 60°; and a knowledge of this fact should tend to modify our usual way of viewing these striations as produced by lateral pressure, acting only at right angles to the strike of the rocks.

Saddles.

Between Clarach Bay and Aberystwyth is a very instructive example of the convex curves of an anticlinal changing into the concave curves of a synclinal, and so producing a saddle (Plate XXVIII. fig. 2). There are all along the coast conclusive proofs of the non-existence of the continuous parallel anticlinal and synclinal folds, which most people, through geological diagrams and sections, are accustomed to suppose really occur in nature. Sectional diagrams can only display the curvatures in the direction of the plane of the section, whereas the curves in nature are really almost as complex as the lines of the hull of a ship.

Core of Anticlinal.

Near Borth, the core of an anticlinal is beautifully exposed, to use Prof. Judd's words, "by the scalpel of denudation." A bed of slaty rock, 4 feet thick, is, without perceptible flaw, twisted round a cylinder of rock perfectly smooth and true, having a radius of not more than 15 feet. This gives one a good conception of the plasticity of the materials of the Earth's crust when subjected to converging pressures under a great superincumbent load.

Plate XXVIII.

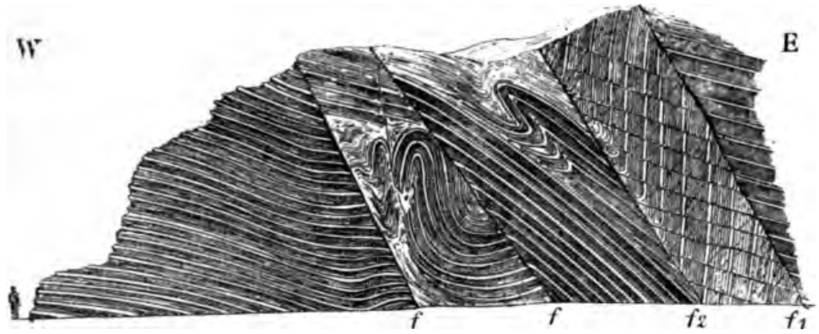


Fig 1

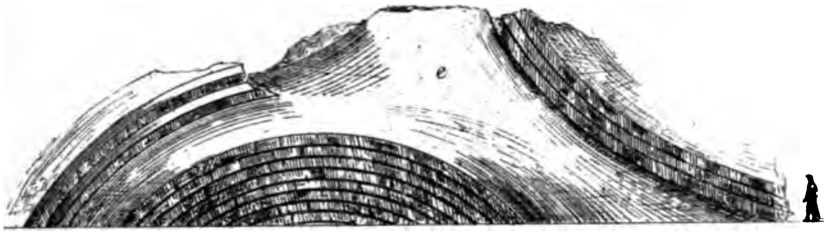
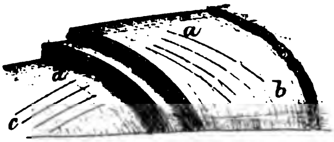


Fig 2.



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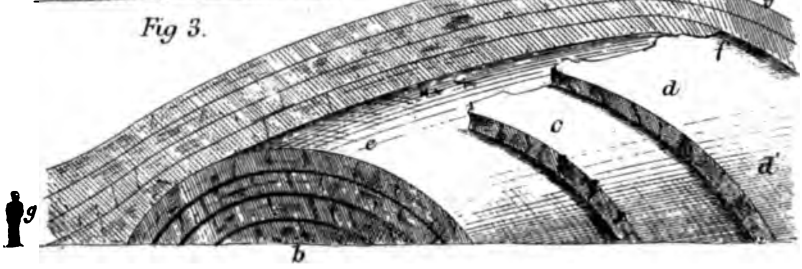
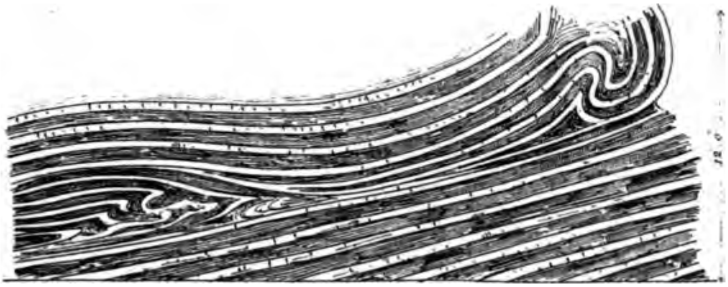


Fig 4.

MELLARD READES ORIGIN OF MOUNTAIN RANGES.

Sprague & Co Photo-Lith London



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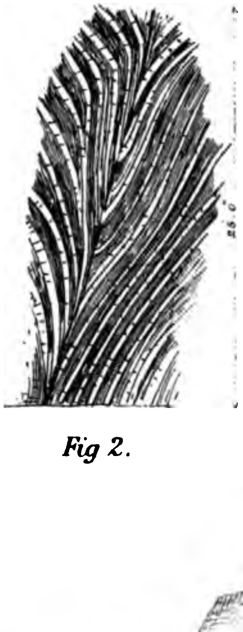

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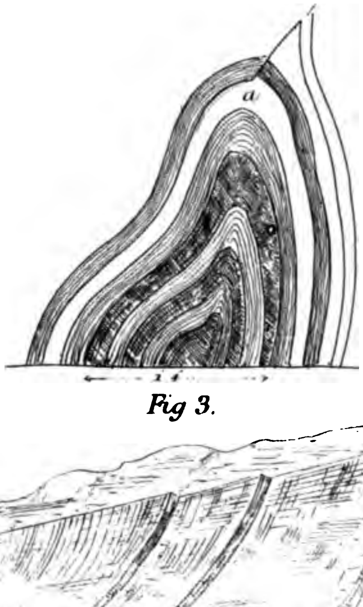

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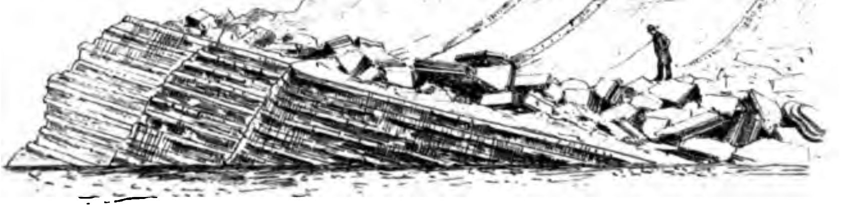
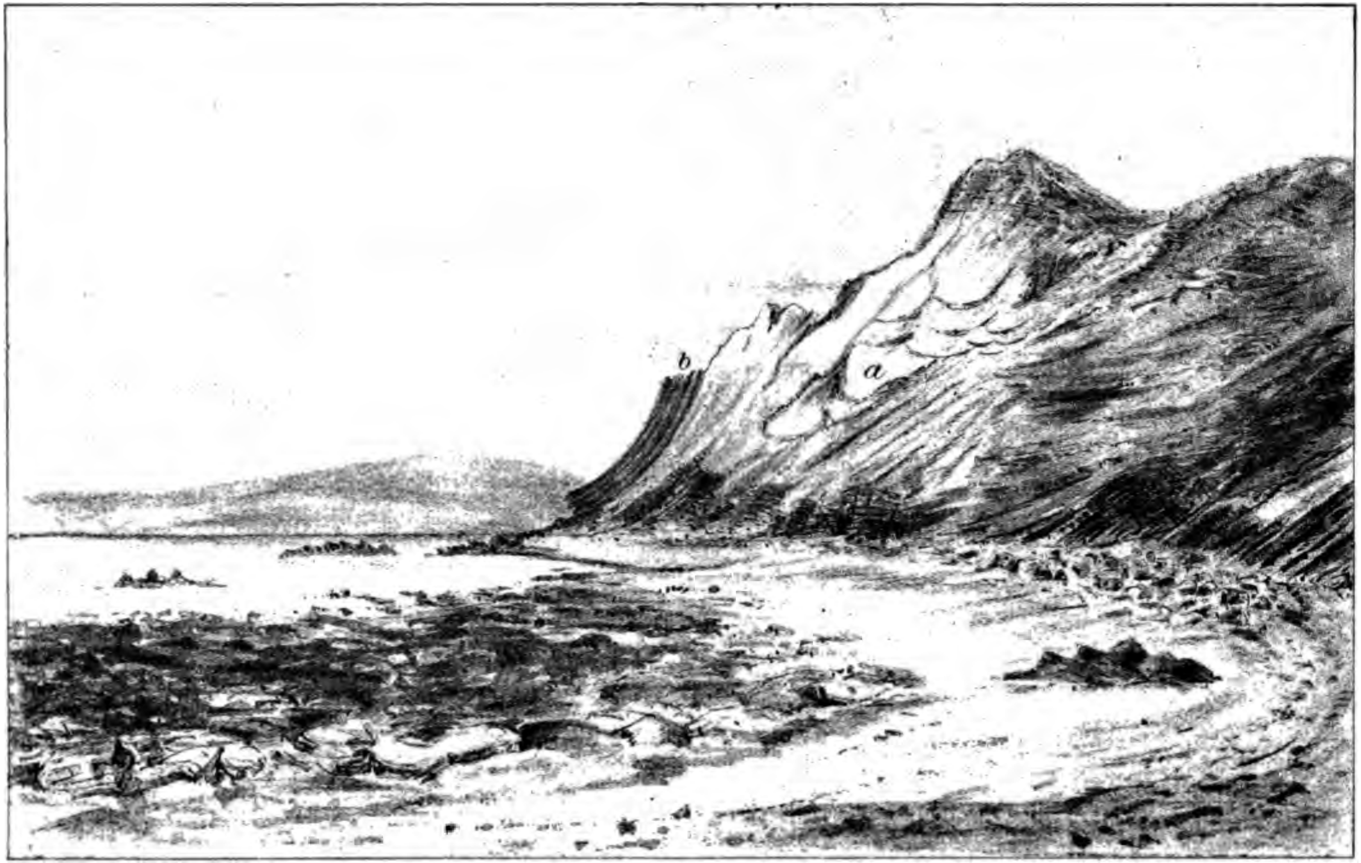


Fig 4.

Sprag. & C° Photo Lith: London

Plate XXX.



MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

Ink-Photo Sprague & Co London E.C.

CLIFFS near BORTH, N. of ABERYSTWYTH.

PLATE XXVIII.

Fig. 1. Section of cliffs of Lower Silurian rocks at Llanrhystyd headland, about 9 miles south of Aberystwyth, showing a complicated set of compression-faults or planes of shearing. (See p. 190.)

Fig. 2. Saddle in Lower Silurian rocks between Clarach Bay and Aberystwyth, formed by the junction of anticlinal and synclinal curves. (See p. 186.)

Fig. 3. Elongated domical anticlinal in Lower Silurian rocks at the north end of Clarach Bay, Aberystwyth. The slickenside striæ *a–b* had a direction S.W. by W.; while those at *c–d*, 12 feet lower in the series, had a bearing N.W. by W. (See p. 185.)

Fig. 4. Domical anticlinal in the station-yard at Machynlleth. The rock is Lower Silurian blue slate, possessing an imperfect cleavage crossing the major axis of the dome at an angle of about 45°. (See p. 191.)

PLATE XXIX.

Fig. 1. Convoluted and contorted rocks produced by horizontal drag. Lower Silurians, cliffs under Alt Wen, Aberystwyth. Explanatory of the convolutions in the Anglesey crystalline schists. (See p. 189.)

Fig. 2. Compression fault under Craig-las, Aberystwyth, formed by the squeezing together of a synclinal. (See p. 190.)

Fig. 3. Small anticlinal under Alt Wen, Aberystwyth. (See p. 189.)

Fig. 4. Synclinal in the Lower Silurian rocks between Borth and Aberystwyth, laid bare by denudation. (See p. 188.)

PLATE XXX.

View of Cliffs in Lower Silurian rocks near Borth, north of Aberystwyth.

At *a* the interior face of a synclinal is seen, of which the lower parts of the beds have been eaten away by the waves, causing the rock to gradually fall away in blocks and slide down to the beach, leaving a sort of frilling round the hill, as shown in the view. It is plainly seen that the synclinal is curved in two directions; otherwise it is of an inverted domical form.

At *b*, the beds of part of the synclinal are seen in section.

The hills in the distance are those about Aberdovey. (See p. 188.)

Synclinals Hollowed out by Denudation.

Towards Borth there are some admirable examples of synclinals laid bare by denudation. In Plate XXIX. fig. 4, p. 187, is a slight sketch of one of them; and in Plate XXX. p. 187, a more finished view of another, showing the general character of the cliffs. The sea having cut almost parallel to the axis of the synclinal, the beds dipping towards the sea have had too great an inclination to stand in that position. Great blocks slip down from time to time and are ground to pieces along the coast by the breakers. The denudation begins at the foot of the slope, and piece after piece of a bed slides away from time to time from the parent bed, which continues to adhere to the rock it lies upon, until in this way it is all destroyed to the top of the slope. This is a curious form of denudation, which leaves while in progress a sort of frill round the cliff, as shown at *a* in the view, Plate XXX. p. 187. As the blocks slide down the inclined plane, they produce rubbings that rather obscure the original slickenside striæ, which are very abundant in most of the beds. The striæ on this synclinal appear to bear N.W. by W., and on the anticlinal further north, N.W. The striations are common to the synclinals as well as the anticlinals.

Complex Convolutions.

It is very difficult to trace out all the complicated curvatures of the strata. One section will disclose beds apparently twisted up into an S-form, or other complex convolutions of the strata. Further complications are caused by faults, not apparently of great throw, but dragging the edges of the strata into sharp curves.

Small Anticlinal.

Under Alt Wen, south of Aberystwyth, I dissected with my hammer an interesting miniature anticlinal, of which I give a section, Plate XXIX. fig. 3. This was composed of gritty slaty beds, without cleavage, and shaly beds. The beds of which it was composed were 1, 2, and 3 inches thick, the height being 1′ 1″, and the base 1′ 4″. It was really the core of a larger anticlinal. The apex, *a*, was bent up into a sharp ridge without fracture, and the materials had evidently flowed in that direction, the beds being thinned on the flanks and thickened at the apex. It is instructive as showing the lengthening the beds undergo by lateral pressure. The inside of one of the flanking grit-bands of the anticlinal showed markings like worm burrows, so that, notwithstanding the pressure, this structure had been preserved.

Horizontal Drag.

Under the cliffs of Alt Wen a striking example of convolution and crumpling produced by horizontal drag is to be seen. I reproduce a section of it (Plate XXIX. fig. 1, p. 187). The section, however, gives but a faint idea of the twists and convolutions of the strata, which, from the light and dark shades of the beds involved, imitate the graining of a large knotty piece of wood. The "twirls" are not in one plane, but curve in various directions, so that a series of parallel sections would all appear different. This throws light upon the extraordinary convolutions of the Archæan rocks of Anglesey, to be presently described.

Horizontal Throws of Faults.

Under Craig-las is a very instructive reversed fault havin a hade 55° E.N.E. and a strike N.N.W. The throw of the fault is 2 ft. 7 in.

A portion of the underface is exposed and on it are slickenside striæ having an angle of 17° with the dip of the bedding measured on the plane of the fault. The interest of this is that the strata on the north-west side of the fault have moved between 8 and 9 feet horizontally to produce the measured throw of 2 feet 7 inches. The shearing force which produced the fault has acted from a north-westerly direction at an angle of not more than 45° to the axial strike of the folds of the district.

Faults by Compression and Shearing.

At Llanrhystyd headland, about nine miles south of Aberystwyth, a complicated set of compression-faults are to be seen (Plate XXVIII. fig. 1, p. 187).

f^1 is a compressed and fractured anticlinal.

f^2 is a compressed and fractured synclinal.

ff are faults, the origin of which is not so obvious. The strata are very much convoluted between the faults. There is very little throw, and the whole of the faults are, doubtless, due to sharp folding, compression, and shearing.

Between f^1 and f^2 the beds are severed and stepped by a set of shearing-planes, having only a small angle with the horizon. The beds are here, as the drawings show, nearly vertical. The upper section has in each case slid in a westerly direction over the section immediately underneath, producing the step-like arrangement of the ends of the beds.

Compression Fault.

Under Craig-las (Plate XXIX. fig. 2, p. 187) is a good example of what I call a compression fault. It is a sharply closed-up synclinal, the beds being broken by sharp bending and compression. It has no measurable throw.

There are many other examples of folds and faults, the general impression left on my mind being that all were due to pressure, or shearing caused by pressure.

Slate-rock at Machynlleth.

In the quarry or cutting of the station-yard at Machynlleth is a good example of the domically-formed anticlinal (Plate XXVIII. fig. 4, p. 187). The sketch shows a section of the core at *b*, where the anticlinal "noses off."

The beds *c* and *d* are seen wrapping round this ellipsoidal dome. The beds at *g*, *g* are shown on the quarry-face; they have originally wrapped round the core also, but have been removed in the quarrying. The back of the dome along the major axis, *e f*, dips 22° N., but is really part of a low curve.

The back of the anticlinal is very smooth and true. The bed at the point *d'* dips 45° N.W. by W. The rock is a slaty rock, exhibiting imperfect cleavage, which dips 63° N.W. The strike of the cleavage therefore crosses the major axis of the folds at an angle of about 45°.

In the Morben Quarry * the beds dip at a high angle to the W.N.W., but it is an inverted dip.

On one of the faces of the beds, which at this point are nearly parallel with the cleavage, I found, in September 1885, beautiful slickenside striæ, having a north-westerly direction. The dip of the bed was 77° N.W. by W., and strike N.E. by N.

At one place in the quarry was a remarkably sharp anticlinal fold, the crushed rock forming the core being crumpled and glossy.

A system of joint planes cuts the rock into prisms, but the inability, from the state of the quarry, to get about rendered my observations incomplete.

From an examination of the débris I found that the cleavage-planes were mostly nearly parallel to the bedding; but in some pieces of rock they were at a high angle to the bedding. This might easily occur from the folding and inversion which the strata have undergone. Mr. W. Keeping * says, for this reason (the approach to parallelism in the planes of bedding and cleavage), "the graptolites usually run for some distance along the surface of the slate, and then gradually skim under it."

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* See Walter Keeping's "Geology of Central Wales," Quart. Journ. Geol. Soc. vol. xxxvii. p. 153.

In a road-section between Morben and Machynlleth the cleavage and bedding, through the trickling of water over the worked face of the rock, have been beautifully etched out. The dip of the beds was here 39° westerly, the cleavage dip 66° N.W. by W. From the great foldings the rocks have undergone through their being in comparatively thin beds, and therefore unable to resist lateral pressure, the cleavage must, in different parts of this district, cut the beds at all angles.

Foldings of Massive Rocks.

Ramsay's splendid and well-known section from the Menai Straits to Aran Mowddwy †, part of which is reproduced in Plate XIV. fig. 3, p. 98, exhibits the effects of compression on Cambrian and Lower Silurian rocks of a more massive type than those just described. This is by comparison a good illustration of the relations existing between the size of the folds and the thickness and massiveness of the compressed beds. Here, instead of small folds, minute anticlinals, or tightly appressed beds, we have whole mountains, such as Snowdon and Moelwyn, but denuded remnants of immense arched masses of strata. That these anticlinals have been produced by a converging or centripetal pressure, acting with a predominating intensity from a north-west and south-east direction, is well evidenced by what is called the Merionethshire anticlinal, a denuded dome occupying an area of over 100 square miles. The whole of the Upper and Lower Silurians have been removed from this space, and mountains over 2000 feet high carved out of the denuded vault of Cam-

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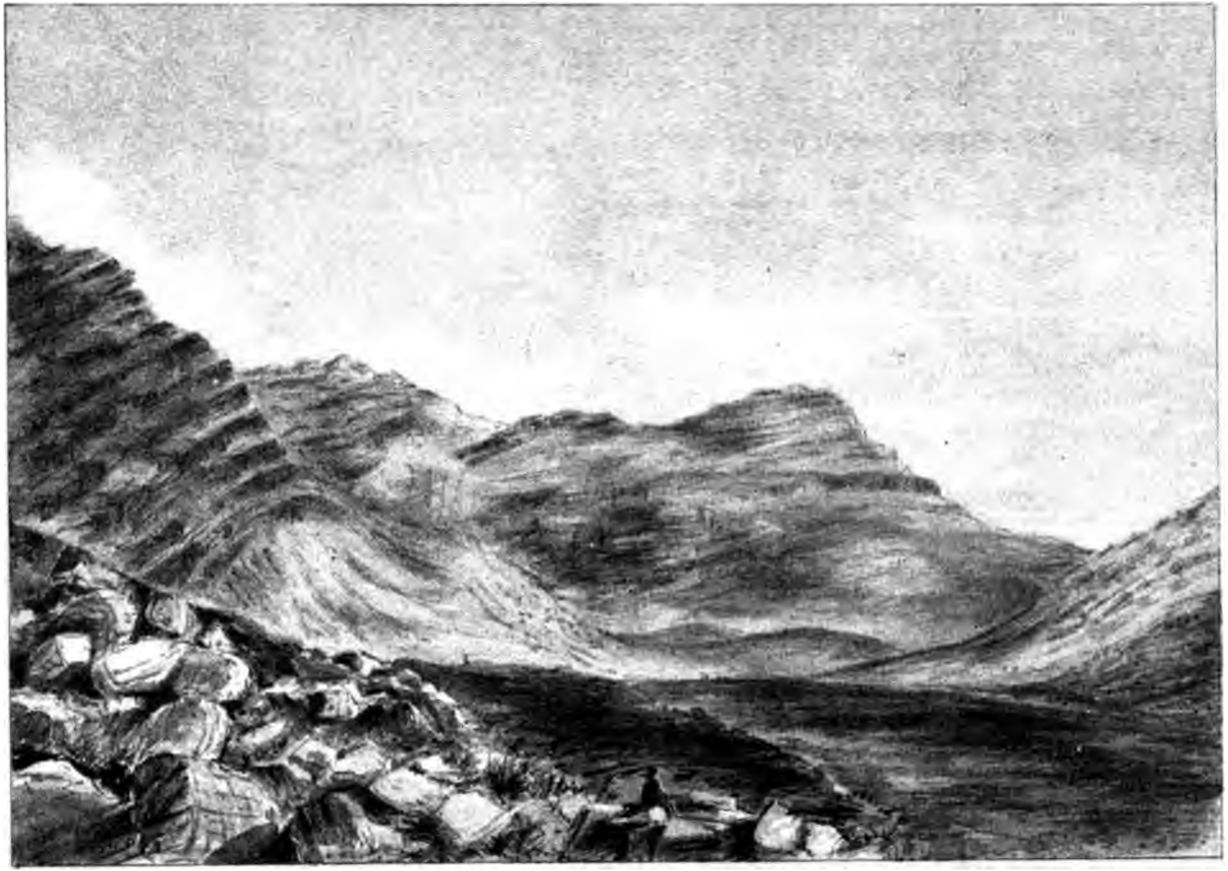
* *Loc. cit.* p. 153.

† Memoirs of Geological Survey, vol. iii., North Wales.

Plate XXXI.



MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

INK-PHOTO SPRAGUE & C° LONDON

BWLCH DRWS ARDUDWY.

brian rocks. The view of the Bwlch Drws Ardudwy (Plate XXXI.) shows this. It is a pass in the heart of the Merionethshire dome, between Rhynog fawr and Rhynog fach. All the strata shown in the view, from base to summit, are Cambrian grits. Excepting to the north-east, where there is a boundary-fault passing near Trawsfynydd, the Cambrian strata disappear under the surrounding Silurians with a quaquaversal dip. In the Snowdon massif immense beds of felstones and ash are involved in the anticlinal and synclinal bendings. The two Manods, near Ffestiniog, reaching in Manod Mawr a height of 2000 feet above the sea, are almost entirely carved out of massive beds of this kind.

PLATE XXXI.

View of the Bwlch Drws Ardudwy (looking north-east), a wild pass in the Cambrian mountains of Merionethshire. This range from base to summit is entirely carved out of the Cambrian rocks forming the Merionethshire dome. (See pp. 192–3.)

ANGLESEY CRYSTALLINE SCHISTS.

The investigation of the bendings, contortions, and convolutions of strata described in the preceding pages will better enable us to understand the more complicated plications and convolutions to be found in the schists of the island of Anglesey.

Sir Andrew Ramsay still considers that the Anglesey schists are Cambrian; but the labours of Bonney, Callaway, M'Kenny Hughes, Hicks, and others * tend to show that they belong to an earlier series. The remarkable lithological change from the Cambrians of Llanberis to the Anglesey mica, chlorite, and quartz-schists, although the distance between them is but a few miles, and the identity between the Cambrians of Llanberis and those of Merionethshire, which are widely separated, incline me to consider the Anglesey schists pre-Cambrian.

For my present purposes it is, however, not very material whether this view be correct or not.

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* "The Archæan Geology of Anglesey," by C. Callaway. Quart. Journ. Geol. Soc. vol. xxxvii. pp. 210–238. Appendix on the Microscopic Structure of some Anglesey Rocks, by Prof. Bonney (1881).

"The Archæan and Lower Palæozoic Rocks of Anglesey," with Appendix by Prof. Bonney. Ibid. vol. xl. pp. 567–589 (1884).

See also "Pre-Cambrian Rocks of Caernarvon," by Prof. M'Kenny Hughes. Ibid. vol. xxxv. pp. 682–693.

"On the Geology of Anglesey," by Prof. M'Kenny Hughes. Ibid. vol. xxxvi. pp. 237–239.

"On the Cambrian Conglomerate of Anglesey and Caernarvonshire," by Dr. H. Hicks. Ibid. vol. xl. pp. 187–208. With Appendix by Prof. Bonney.

"On the Pre-Cambrian Rocks in Caernarvonshire and Anglesey." Ibid. vol. xxxv. pp. 295–320.

"On the Metamorphic Series between Twt Hill (Caernarvon) and Port Dinorwig," by Prof. Bonney and F. T. S. Houghton. Ibid. vol. xxxv. pp. 321-326.

"Some New Points in the Pre-Cambrian Geology of Anglesey," by Dr. C. Callaway. Geol. Mag. 1880, pp. 117-127. With Appendix by Prof. Bonney.

Cemmaes Bay to Bull Bay.—On the north coast of Anglesey, between Cemmaes Bay and Bull Bay, the folding and structure of these ancient schists can be well observed.

The strike of the beds is generally in a west by north and east by south direction, though there are, according to my observations, more local variations than are shown on the Survey Geological Map.

It is evident that the dominant pressure acted in a northerly and southerly direction.

This is shown by the pressure-faults, the planes of which dip northerly, and by the slickenside striæ to be seen in the limestone-quarry at Porth Badric.

This quarry in the Cemmaes crystalline limestone is in itself very instructive; for, notwithstanding its apparent obliteration, the bedding is clearly discoverable by these slickenside surfaces.

Here again, though the dominant pressure acted on a north and south line, the several domes in the quarry on which the striæ occur show that the pressure was also centripetal. The striæ are parallel, or nearly so, throughout the quarry, being magnetic north and south. There is also a fault with a very low hade, the apparent dip being west north-west. At the headland north of Porth Badric there is a fault or slide, having a low hade to the northwards.

West of the China quarry is a very remarkable conglomerate, consisting of quartzite pebbles in a laminated or foliated matrix, the laminæ of which bend round the stones. The westerly part of this conglomerate looks exactly like a breccia. A close examination led me to suspect that this breccia was produced by the crushing of the quartzite pebbles, the individual pieces fitting together like mosaic, but having a general parallel linear arrangement in the direction of the bedding. West of Bull Bay the strike of the rocks in the headland is north-west and south-east, the dip where I measured it being 48° N.E. Again, at a point west of this the strike of the rocks where I took my observation was E.N.E. and W.S.W., with a dip of 74° N.N.W.

The strike of the rocks is east and west in Bull Bay, the dip 45° N. On the edges of the beds, as shown in Plate XXXII. fig. 4, p. 197, are seen a series of pleats and folds, their axes on a horizontal plane being parallel, bearing S.W. and N.E., as shown.

The rocks are divided by a system of north-and-south joints, along which the erosive action of the waves cuts deep gashes into the rocks, helping to give the rugged character distinguishing this coast-scenery.

Point Ælianus.—South-east of the lighthouse on Point Ælianus (or Linas) there are excellent examples of convoluted rocks. The strike of these convolutions can be readily traced on a horizontal plane (when the rocks are worn down in that way). The strike of their axes is N.E. and S.W., or from that to N.E. by E.

On these rocks are also to be seen evidences of movement by pressure-faulting. One of these faults had a strike E. and W., the striæ there bearing N.E. and S.W., dipping 39° S.W. Another set of slickensides that I observed had the striæ S.E. by S. and N.W. by N., dipping 12° N.W. by N. Another example was N.W. and S.E., and horizontal.

I am of opinion that what Ramsay calls the "foliation," generally speaking, represents the lamination of the bedding. The horizontal platforms on which the striæ occur are probably joints.*

In a small quarry at the top of the cliff, by the entrance to

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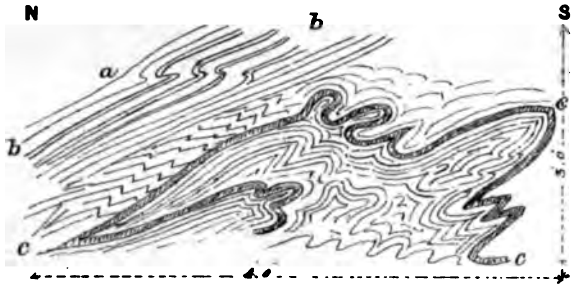
* Sedgwick, speaking of the foliated rocks of "Holyhead Mount" and similar schistose rocks elsewhere, says—"In general, however, the foliated uneven layers of these older formations belong, I believe, to beds, and not to cleavage planes, and the oldest and most crystalline rocks, designated by the general name of Schists, have no true slaty cleavage, in the sense in which I have used the term" ("Structure of large Mountain Masses," Trans. Geol. Soc. 1835, p. 479).



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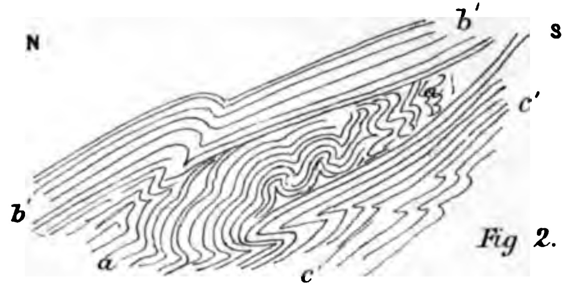

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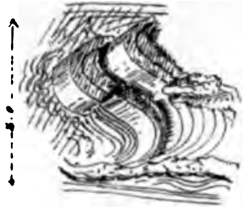

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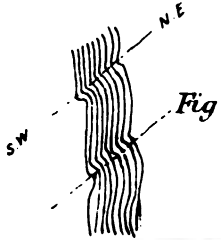

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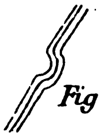

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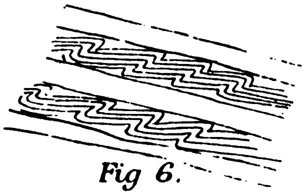

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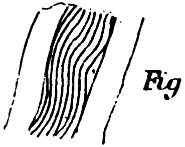

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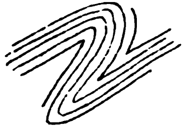

Fig 8.

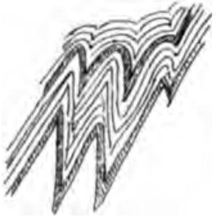

Fig 9.

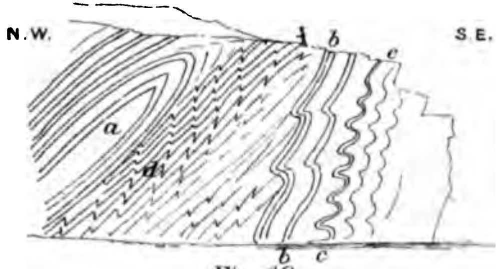

Fig 10.

Sprague & Co. Photo-litho. London

PLATE XXXII.

Anglesey Crystalline Schists.

Fig. 1. Sketch of convoluted structure shown in a section on the east side of road from Holyhead to Porth dafarch, described p. 199.

Fig. 2. The same, taken a little further south. The face of both sections is a joint plane. (See p. 199.)

Fig. 3. Convoluted structure, simulating architectural bracket, Porth dafarch. (See p. 200.)

Fig. 4. Plan, showing the edges of the schists on a horizontal plane (Bull Bay) and the puckering in a S.W. and N.E. direction. (See p. 196.)

Fig. 5. A plate of the schist showing the nature of these puckers (p. 199).

Fig. 6. Soft laminated beds enclosed between harder beds, showing how the frilling is supposed to have taken place by horizontal drag. (See p. 199.)

Fig. 7. The same, less developed.

Fig. 8. A common structure in the convoluted rocks.

Fig. 9. Chevron-folds as displayed in a joint plane S.E. corner of Porth Eilian (Point Ælianus). (See p. 198.)

Fig. 10. Sketch of a cliff-section west of Porth dafarch, showing how the peculiar structure of the minute convoluted foliations shown in the previous figures is reproduced on a large scale in the bedding of the rocks. (See p. 200.)

PLATE XXXIII.—FRONTISPIECE.

View of convoluted schists in the cliffs opposite the South Stack, Holyhead, looking to the north-east. The distant cliffs are those of Holyhead Mountain. (See p. 198.)

the lighthouse enclosure (south-east angle of Porth Eilian), are to be seen some remarkable and minute plications or foliations (Plate XXXII. fig. 9, p. 197). These so-called folia are plicated into very sharp folds (chevron-folds). The folia will separate on being struck with a hammer, so that in some cases a series of anticlinal and synclinal mountains are simulated on a very minute scale in a hand specimen. These convolutions, from the different colours of the mineral bands, show very distinctly on the joint planes. The plane of the sketch (fig. 9) is a joint plane. These joint planes frequently have polished surfaces, and the rocks split as if coarsely cleaved.

The same peculiarity I have noticed in slate-rock, which will be described in the Chapter on Cleavage.

At the north-west angle of Point Ælianus the strike of the rocks is east and west, dip 62° N. On these rocks I observed slickenside striæ, having a direction N.W. and S.E., and dipping 37° N.W.

Holyhead Island.—At the South Stack the folding of the rocks is truly remarkable. (Plate XXXIII. is an Ink-photo of a sepia sketch I made this year, 1886; from it a good general idea can be obtained of the remarkable plications, and even torsions, these rocks have undergone.)

The sketch (Plate XXXIV. fig. 1) shows the "festooning" of the beds of rock opposite the South Stack, from a point of view directly at right angles to the plane of the cliff. At *a* the beds are shown on the plane of a joint, the line *b* representing a joint at right angles thereto. This can be understood on reference to the view (Plate XXXIII.). At *c* a recent slip had occurred, exposing fresh faces of the joint at a higher level. The whole of this gash at *a* is due to the undermining of the waves and the slipping of the overhanging rock down the joint-planes.

The hard quartzose bands at *d d* have a rude cleavage, as shown in the sketch, not parallel but affected to some extent by the plications. From the softer and argillaceous nature of the intervening bands of rock, these festoons stand out by weathering in a striking manner. It appears pretty evident that the extraordinary ribbon-like bendings of the festoons arise from the hard nature of the quartzose bands and the soft nature of the intervening beds. The one gives way by puckering, the other by plastic movement. It is not improbable that the greater expansibility of the more puckered bands may also have had its effect.

The strike of the strata on the South Stack is E.N.E. and W.S.W., and they were vertical at the point where I took the observation, but, from the numerous convolutions, the dips may vary at every point.

The massive beds are in the largest folds, and the laminated softer beds between them are often frilled, as shown in figs. 6 and 7, Plate XXXII. Fig. 5 is the representation of a small piece of lamina chipped off the rocks, given to illustrate the nature of the small folds that occur in thin but straight beds, as at *a*, fig. 1. About a mile south of the South Stack, on Lord Stanley's grounds, is a fine example of an overturned synclinal (Plate XXXV. fig. 1, p. 203). It exemplified in a striking manner the thinning of vertical beds by lateral pressure, and the thickening at the bends from the same cause. The bed at *a* is only one sixth the thickness of the same bed in the synclinal bend at *b*. A massive greenstone dyke occurs at *c*. The face of the cliff, as shown in sketch, is nearly parallel to the dyke, or north-west and south-east.

On the road from Holyhead to Porth dafarch, in a cutting on the left-hand side of the road, is a most interesting example of convoluted foliation.

Parts of this are shown in Plate XXXII. figs. 1 & 2, the face being a joint plane.

I satisfied myself that the folia represent the original plane of lamination. At *b b*, fig. 1, and *b' b'*, fig. 2, the laminations of the bedding are quite apparent, having a regular dip to the northwards, thus showing that the strike agrees with the general strike of the strata in Anglesey, which is in a west and east direction. At *a*, fig. 1, there is a series of double folds. These have evidently been produced in the way Daubrée, by his experiments, shows such folds are originated in beds of rock. The very involved folds of the laminæ at *c*, *c*, *c*, fig. 1, and the foliations they enclose have doubtless been produced in the way the convolutions at Aberystwyth (Plate XXIX. fig. 1, p. 187) were produced, namely, by horizontal drag and squeezing together between more massive beds to the north and south. The same explanation applies to the foliations at *a a*, Plate XXXII. fig. 2, and the more regularly dipping laminæ enclosing them at *b′ b′*, *c′ c′*.

As an instance of the curious bendings and flowings that have affected the beds of rock in the Anglesey schists, I may point to Plate XXXII. fig. 3, representing a convoluted structure to be seen at the side of the road at Porth dafarch (right-hand side), where architectural brackets are well simulated. The strike of the rocks here is N.E. and S.W.

That the minute convolutions of the folia are identical in character with the larger bendings of the bedding, we have a good proof in the sketch, Plate XXXII. fig. 10, which represents the side of a cliff west of Porth dafarch, the observer looking towards the north-east. At *a* the beds show in a sharp overturn anticlinal. At *b* the beds have the same direction of dip, but are folded vertically. At *c* the folds become vertical festoons. At *d*, between these more massive beds, we have thinner beds pushed up into sharp chevron-folds by the upward drag of the overturn anticlinal now resting upon them. It is probable that the festoons at *c* were produced before the beds were overtilted.

One peculiarity of these extremely interesting cliff-sections is the proximity of perfectly regular anticlinal and synclinal bendings to strata having the most extraordinary convolutions. An instance of this is given in the sketch, Plate

XXXV. fig. 2, in which *a* and *b* are overturned anticlinals with a closely appressed synclinal *c* between them from which the matter has been squeezed out and has flowed in a fan-like form towards *d*.

This is a clear proof that the serpentine scrolls, as at *e e*, are due to combined bending and flowing, and helps us to understand the origin and structure of the minute convoluted foliations. The axis (*f g*) of the anticlinal (*a*) which, if completed, would be an elongated dome, is S.W. and N.E., the same as the strike of the rocks at Porth dafarch.

To conclude this description, the cliff-sketch at Porth-y-gwin, Plate XXXIV. fig. 2, shows this juxtaposition of serpentine convolutions on a large scale, *a a*, with part of a regular overturn anticlinal *b b*, which graduates into a smaller overturned loop at *c*.

It will thus be seen that in a structural sense the Anglesey schists are extremely interesting. The mineralization of that which, for want of a better term, we may call with Ramsay the "folia," is doubtless, in many cases, subsequent to the convoluting.

As I have shown, these convoluted folia to a great extent are only reproductions on a small scale of what takes place in the bedding on a large scale. It is indeed quite inconceivable to me how such convoluted laminæ could be produced if there were not a pre-existent lamellar structure to convolute.

This lamellar structure was certainly not cleavage, nor could convoluted laminæ be produced by flowing. A flow structure is the result of the movement of the constituent particles of the substance along definite planes. Lamination might be produced first in this way, and afterwards, by the action of other forces, the laminæ might become convoluted; but there is no collateral evidence of any such sequence of events having taken place.

The schists of Anglesey have doubtless been affected by horizontal pressure at several periods of geological history.

The changes in the strike, the regular anticlinal and synclinal structure occurring in some places, and the convolutions, bendings, and twistings in other localities bear witness to this. The striæ on the joint planes and fractures, and in some cases on the bedding, are equally eloquent in telling the same story. That the schists have been covered by enormous masses of rock, since removed by denudation, is not less plain. The verticality of the cleavage in the Llanberis slate-quarries is one evidence of this; for these Cambrian slates could not have been subjected to the horizontal pressure requisite to produce them had they not at the time of their birth been buttressed up with masses of rock overlying the Anglesey schists.

PLATE XXXIV.

Fig. 1. Front view of the cliffs opposite the South Stack, Holyhead. *a* is the face of a joint plane, showing very truly the bendings and festooning of the beds.

This is the same as the rectangular gash in the rocks to the right of the picture (Plate XXXIII.), caused by the slipping-down of the rock along the joint planes *a* and *b*.

There is a curious association of festooned beds *e* and *d* with regular flexures *c* and *f*.

The beds *d*, *d* are hard, and affected by a rude cleavage strongly brought out by weathering; it is not parallel but is partially affected by the plications of the beds. The intervening beds are soft and strongly weathered out, giving the cliff a very remarkable appearance. Beds of similar character to those described reappear at *g* on the right hand side of the fault *f*. (See p. 198.)

Fig. 2. View of cliff at Porth-y-gwin. The most extraordinary contortions are observable in this cliff; the beds at *a*, *a* are more comparable to contorted notes of interrogation than to anything else I can think of.

Notwithstanding this, we see at *b* the remains of a strong and perfect overturn anticlinal. It looks as if the rocks here had been first regularly folded and then "mashed" up by after movements.

If the rocks were first folded in Archæan times the mashing-up, twisting, and vertical tilting of the plicated beds, as at *a*, *a*, was most probably synchronous with the uplifting of the Snowdonian range. (See p. 201.)

Plate XXXIV.

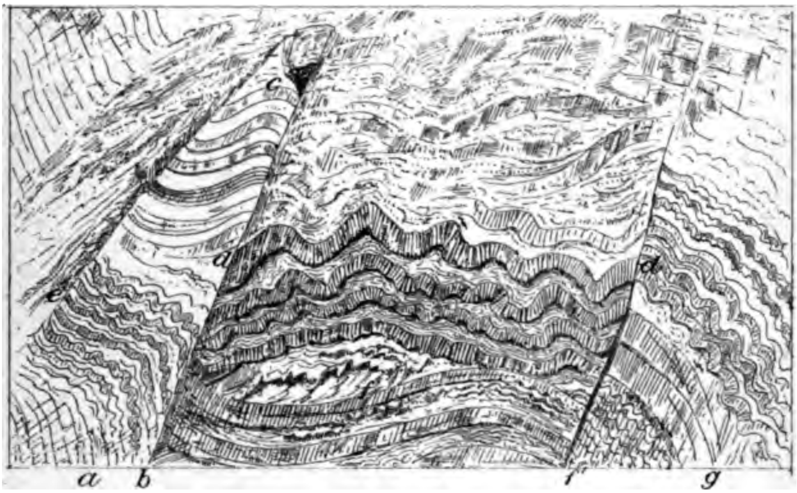

Fig. 1.

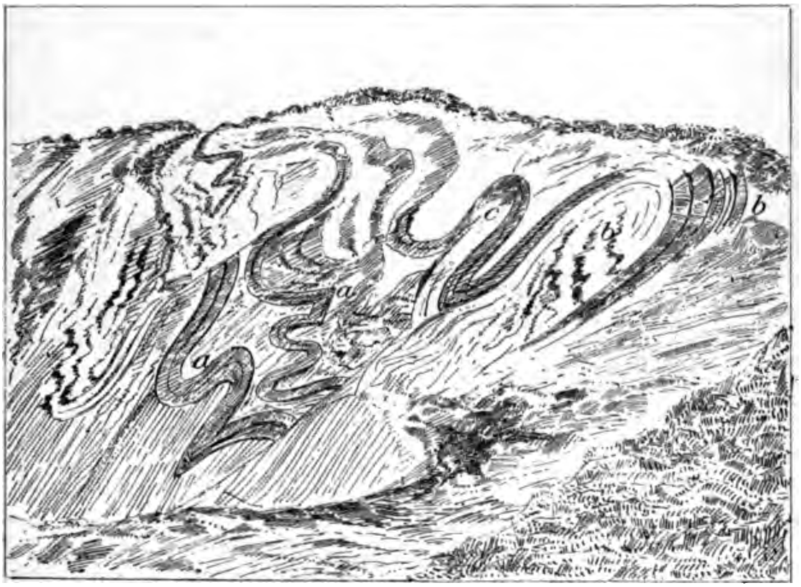

Fig. 2.

MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.
Sprague & Co Photo-litho. London

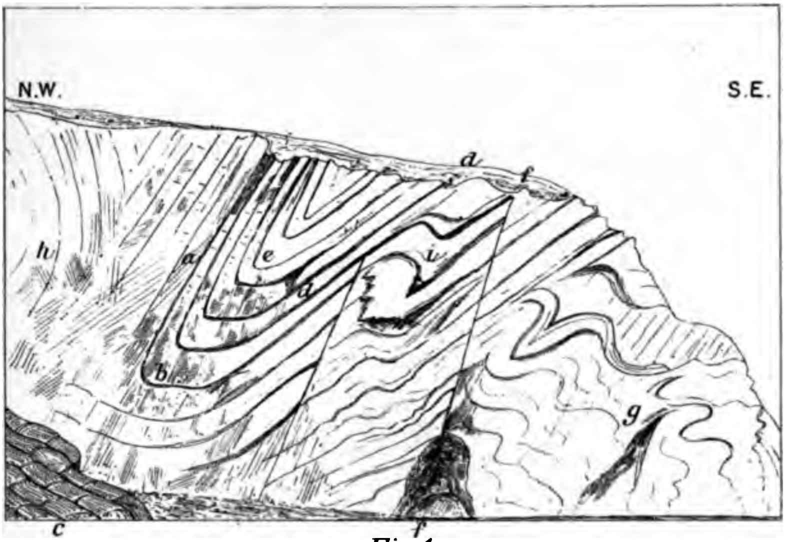

Fig. 1.

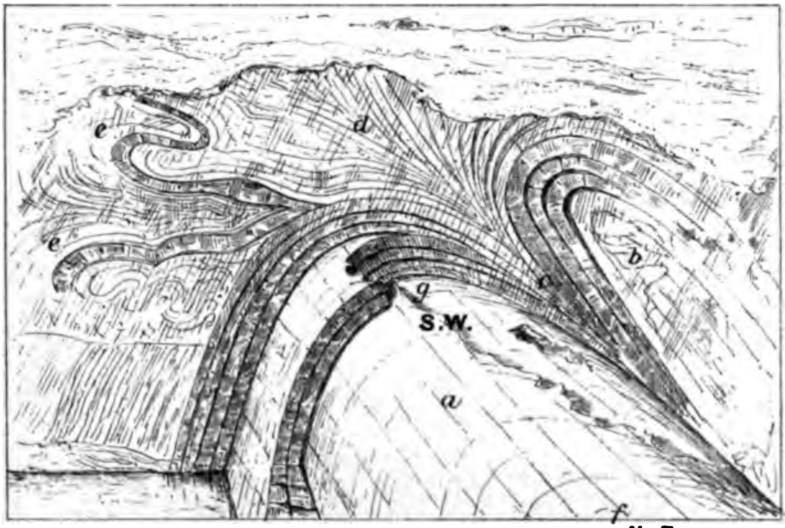

Fig. 2.

Sprague & Cº Photo-litho. London

PLATE XXXV.

Fig. 1. Overturn synclinal in a cliff on Lord Stanley's grounds, about a mile S. of the South Stack.

This is a splendid example of the extension of beds by compressive strain, the left limb of the syncline at *a* being only one sixth the thickness of the bottom bend at *b*. A similar thinning of the bed by pressure occurs on the opposite limb at *d d*, while at the bend *b* the beds from *b* to *e* have all been thickened. At *f f* is a fault with very little, if any, throw. At *g* and *h* the beds are "mashed" up. From the bend at *i* it is inferred that the whole syncline has been pushed up in the direction *d d*.

At *c*, in the corner of the sketch, is seen the basalt-dyke, along the side of which the sea-gulley, exposing the clifi, has been excavated. This dyke crosses the bay in a south-easterly direction, reappearing in a striking black tower (due to its denudation) on the opposite shore.

Fig. 2. View of overturn anticlinals in a creek W. of Porth dafarch. The core of one of them is preserved as shown, the axis *f y* bearing N.E. and S.W. The strata have been as it were peeled off the core. At *c*, the beds of the syncline have been squeezed out in a fan-like form. Outside, and surrounding these remarkable anticlinals, the strata are mashed up into extraordinary convolutions. (See p. 201.)

COAL-BASINS.

The term "coal-basin" implies a concave form of bottom which does not accord with the prevalent idea of a synclinal trough. The reason why coal-beds usually lie in basin-shaped hollows is because they have been subjected to converging pressure, and not because they were originally laid down in that form. It is here maintained that the basin-shape is the normal condition of synclinally flexed strata. In consequence of coal being an article of great commercial value, more is known of its mode of occurrence than perhaps that of any other mineral bed. Any section in any direction across an anticlinal or synclinal necessarily shows in an arch or inverted arch form. In coal-strata, through following out the beds, it has been found that these arch-like sections are merely sections of more or less elongated elliptical troughs.*

An interesting plan and section of the Goyt trough, in North Staffordshire, is given by Prof. Green †, which will assist to explain the nature of a synclinal trough. If it were possible to map out all conterminous beds that have been affected by horizontal pressure, we should find that synclinals generally assume—allowing for faults and disturbances of after occurrence—more or less this basin-shape.

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* Prof. Hull recognized this fact long ago, although his explanation is not quite the same as mine. In the following I should substitute *centripetally* for "along two systems of lines."

"It must not be supposed, however, that this basin-shaped arrangement of the Upper Carboniferous strata was the original form in which the coal-fields were deposited, like so many lakes filled with sediment and surrounded by hilly banks and barriers. Such an idea would be altogether erroneous. The basin-shaped structure is in every instance due to terrestrial movements acting along two systems of lines, accompanied and followed by denudation." ('Coal-Fields of Britain,' 3rd edit., p. 463.)

† 'Physical Geology,' 2nd edit., pp. 480–1.

In Pennsylvania, from the parallelism of direction of the dominant pressure which created them, the coal-basins are mostly canoe-shaped troughs. The beautiful maps in the grand Atlas of the Anthracite Coal-fields of Pennsylvania, by Prof. T. P. Lesley and Chas. A. Ashburner, very ingeniously show the form of each basin-bottom by a series of subterranean contours 50 feet apart.

From this we see that the basins are elongated synclinal concavities, the major axes of which are often from 10 to 50 times that of the minor axes.

In some cases, for example the Mahanoy Basin, the synclinal concavity in cross section presents the appearance of a V with the bottom sharply rounded off. Alongside of this is a synclinal having a well-curved section, or, as is the case in the example given in Plate XXXVI. fig. 2, p. 207, there may be a repetition of a V-fold with an overturn anticlinal. Sometimes the strata present the appearance of a series of sharp folds (chevron folds), as if several beds had been folded up on hinges, or they may assume long curved folds, as in Plate XXXVI. fig. 1. In all cases, however, the folds resolve themselves into anticlinal convexities or synclinal concavities. The proportions of the major and minor axes of these elongated troughs differ according to the intensity of the dominating pressure which created them. Some of the Mammoth-bed coal-basins appear to be long troughs with the bottom in undulations produced by minor concavities, often several hundred feet below the lowest point of the lip of the main trough.

To thoroughly understand the complexities of these coal-bottoms, the maps themselves should be studied. It will then be seen that, complex as they are, continuity of curvature is preserved in every direction. It seems clear that though the dominating pressure has been at right angles to the trough, there has also been pressure along the major axis, and indeed in more or less intensity from every point of the compass.

Panther-Creek Basin.

A photograph of a plaster model of this coal-basin copied in lithography is given in the First Report of Progress in the Anthracite Coal-Region, 1883 (Chas. A. Ashburner), p. 242. Of this model, Prof. Lesley says:—"The most striking feature of the plication of the coal-beds of this basin is its sharpness, the rarity of those soft and gentle curvatures which characterize the bituminous coal-basins, a rigid plainness of the up and down slopes, suggestive of a severe lateral compression in the jaws of a vice, and a humid plasticity of the Coal-measures at the time of compression" *. Prof. Lesley is of opinion that "no Palæozoic plication occurred until the close of the Coal age; and that it took place then at once, and for all."

Floor of the Mammoth Bed.

In the large Atlas before referred to, an underground contour-map, showing the shape of the floor of the Mammoth bed at Maunch Chunk, is given, together with a photo-lithograph of a plaster model on the same scale. An examination of Plate XXXVII. figs. 1 and 2, will enable the reader to realize the nature of these great synclinal troughs. The plate is an Ink-photo of part of the Atlas-sheet, and therefore an exact reproduction (on a smaller scale) of the original. Some of the references on the map relate, it is necessary to observe, to other portions of the Atlas not copied. As all the information requisite for understanding the plate is contained on it, it is unnecessary, in this instance, to give a separate detailed description.

The same remarks apply to Plate XXXVI.

Variations in Thickness of Beds by Pressure.

Prof. Lesley suggests that the extraordinary variations in thickness in the conglomerate of the southern field of the

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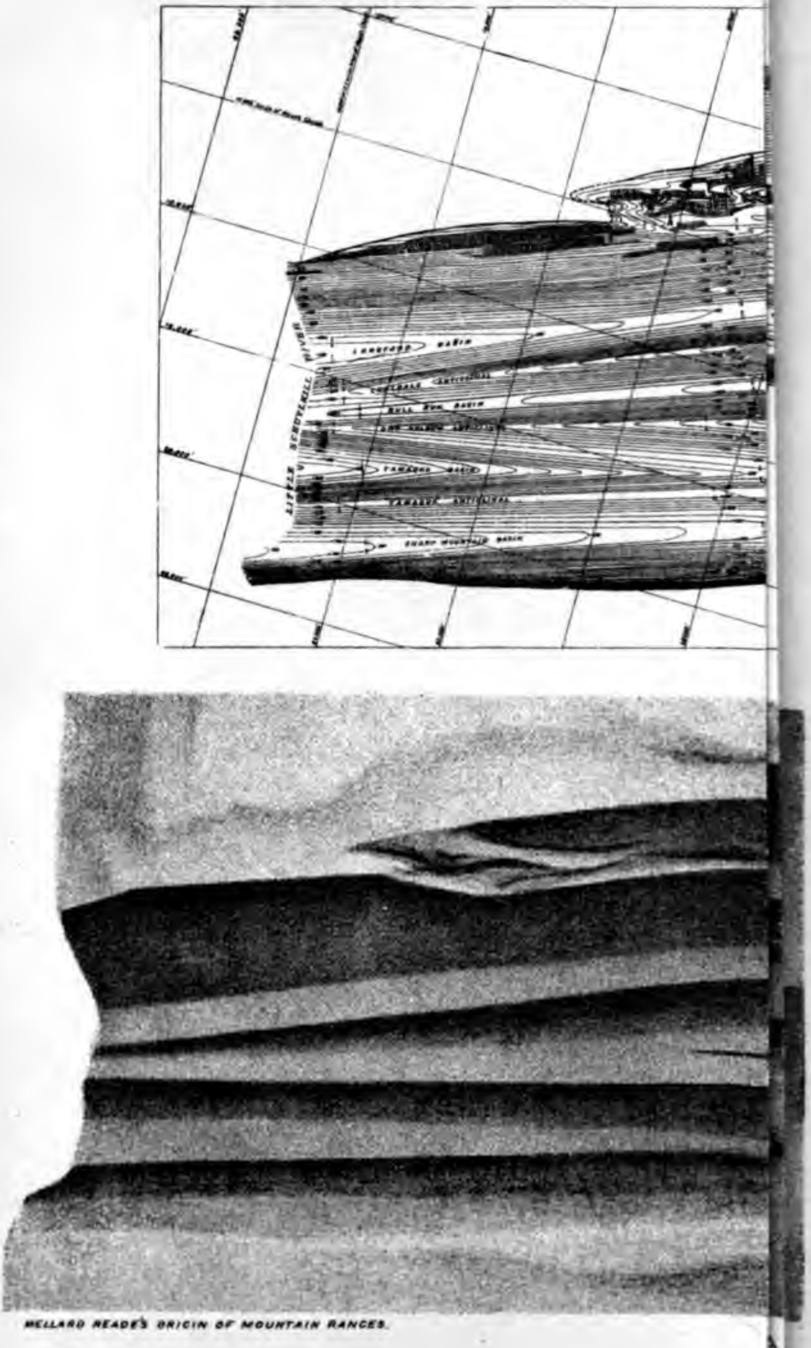
* Second Geological Survey of Pennsylvania, p. xviii AA.



MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

PLATE XXXVI.

Sections of Anthracite Coal-fields.
(Reproduced from the Second Geological Survey of Pennsylvania.)

Fig. 1. Section through the Shenandoah, Ellangowan, and Mahanoy Basins.

Fig. 2. Section through the Shenandoah, William Penn, and Mahanoy Basins.

PLATE XXXVII.

Plan and Model, showing the Floor of the Mammoth Beds in the Anthracite Coal-field of Pennsylvania. (Reproduced from the Second Geological Survey of Pennsylvania.)

Fig. 1. Plan of Floor of the Mammoth Bed, with contour lines at every 50 feet vertical.

Fig. 2. View of the Model, exhibiting the plications in the above.

Anthracite region, although in other regions throughout Pennsylvania it has a pretty uniform normal thickness of 300 feet, is due to the same cause as the local bulging of coal-beds and the shales and sandstone intervals. He states that along some miles of the western end of the Dauphin County coal-basin, the basal layers of the conglomerate which form the crest of the mountain are tightly pinched, like the Panther-Creek Coal-measures; and it is possible that such pinching occurs along the line of every sharp synclinal in the Pottsville basin. The local vertical variations in thickness are from 1700 to 900 feet, and back again to 1700 feet. Prof. Lesley points out that if both top and bottom planes of the conglomerate are sharply plicated, it is evident "that there must have been a universal shifting of all the materials of the formation, both in various directions and in various degrees commensurate with the irregular construction, imperfect parallelism, and diverse amplitude of the different folds." *

According to Mr. Ashburner, whose surveys of this complicated region are models of scientific care, the Anthracite coal-beds are subject to such unexpected and inconceivable freaks in the numerous foldings which they make, that it is frequently impossible to even suggest a solution of the structure.

Pinching-out of Coal-beds.

Frequent references are made by Mr. Ashburner to the "pinching-out" of coal-beds, which is of not uncommon occurrence; and a further proof, if that be wanted, of the internal movements of the coal consequent on pressure. The existence of pockets of coal also point to the same great fact. Pinching, dispersion, thickening, or pockets are all the results of a change of mass by flowing. After what M. Tresca has taught us of the "flowing of solids," it seems hardly necessary to postulate for the phenomenon any specially soft condition or plasticity of the coal itself.

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* Second Geol. Survey of Pennsylvania, p. xix AA.

Surface Areas of Coal-basins as compared with the Areas of the Beds.

The relation between the area of the surface and that of the coal-bed has been carefully computed in a good many cases by Mr. Ashburner. They seem to range in the proportion of 12 of surface to 19 of coal-bed. How much of this is due to simple folding and how much to actual extension of the beds it is impossible to estimate. Even in estimating the quantity of coal in a certain district, there is a great element of uncertainty in the difficulty of assigning an average thickness to the coal-beds *. The Mammoth bed varies from 27 feet to 102 feet thick.

Internal Changes involved in the Folding of Beds.

Strata cannot be flexed or folded without corresponding internal changes taking place in the beds themselves. Irrespective of molecular change, the material of the bed must distribute itself in a way to meet the surrounding pressures and tensions to which it is subjected. Let us investigate a few examples.

Simple Flexure.—The simplest form of change is the angular bending of a bed upon itself as in a V-shaped anticlinal or synclinal.

Prof. Miall showed, in a series of very ingenious experiments, that thin slabs of limestone, if acted upon by weights properly proportioned and placed, could be bent to a considerable angle without fracture. By means of an apparatus which could be gradually loaded by the addition of shot, he succeeded in one case in bending a plate of limestone ·07 inch thick to an angle (reckoned as rectilinear) of 12°. This took three months to accomplish. *Time* was found to be one of the essential elements of success. On removal from the machine the plates generally cracked at the apex in a few days *.

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* P. 109 AA.

In the Earth's crust a sharp simple flexure of a bed occurs under different conditions. Here, all the surrounding rocks are in a state of stress, pressing upon and supporting one another. I have little doubt, however, that the bending takes place around a neutral axis, above which, in a synclinal, the bed is in a state of compression, and below it in a state of tension (see Plate XXXVIII. fig. 4). In consequence of the pressure of the surrounding rocks, with which the bed is in perfect contact, the tension seldom ends in a rupture, the material of which the bed is composed being extended by squeezing.

With a series of beds affected in this way, each bed is acted upon in a similar manner, and the beds otherwise adjust themselves to changing conditions of space by sliding upon or over one another. In a closely compressed synclinal the beds in the core must be actually squeezed upwards as in the jaws of a vice.

To illustrate how beds slide on each other in adapting themselves to varied foldings, a very simple and neat experiment may be made.

Take a series of strips of paper, all exactly the same width and length, then mark across the edges at intervals of half an inch a succession of parallel lines. The strips must be held tightly together between boards while this is being done. Then place the series, edges downwards, on a board, and fix the centre by gripping it between two pieces of wood, as in the diagram (see Plate XLII. figs. 1 & 2, end of book).

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* 'Popular Science Review,' January 1872.

By the aid of French nails driven into the board at any determinate points, the compound strip can be bent backwards or forwards at pleasure.

The parallel lines previously marked at right angles to the outside planes (fig. 1) now show at a variety of angles (fig. 2), according to the form of the folds. These angles exhibit the extent to which the beds have moved upon each other. The illustration is taken from an actual example.

Squeezing or Stretching-out of Overfolds.—In some cases it is impossible to account for the form the folds assume, except by actual squeezing-out and lengthening. This is shown in an overfold of the before-mentioned Mahanoy anticlinal in Pennsylvania (Atlas, Sheet AA 21, Section No. 3). If we produce the folds, we shall find that the strata have been gripped between two synclinals, and that the top beds are longer than the bottom; hence either the one has been stretched or the other shortened, the former being the true explanation. In Atlas, Sheet AA 22, Section No. 5, the Mammoth bed, in the underpart of the overfold of the Shenandoah anticlinal, is very much thinner than the continuation of the same bed on the back of the overfold. Most probably it has been extended on the underside. The contrast between the sweeping circle of the Locust-Mountain anticlinal and the extraordinary V-shaped trough of the adjoining Mahanoy synclinal in Sections Nos. 7, 8, and 9, Sheet AA 23, is very striking. Also the fan-form of a series of beds to the right of Section No. 9.

From the convexities and concavities into which the beds are moulded, as previously explained, the movements have been still further complicated. Although the synclinals are often such long canoe-shaped troughs, an examination of the underground contours, which so admirably display the form of the bottom, shows that pressure has acted along the longer as well as the shorter axis, but in a much less degree. (See termination of Mahanoy basin, Western Middle Coal-field, Mine Sheet No. 1, also Mine Sheet No. 2*.)

Anticlinal of Brady's Bend.

In the Bituminous Coal-fields of Western Pennsylvania, the declination of the axes of the anticlinals has in some cases been measured.

This declination is doubtless part of a low curve forming the longitudinal back of the anticlinal, indicating that the typical but extremely elongated domical shape also prevails in this district.

Taking the Upper Freeport coal as a horizon, the altitude of the crest of the axis of Brady's Bend anticlinal on Little Buffalo, near Saxon City, is 1175 feet above the tide; and at Wood's run, where the axis crosses the Ohio River, the same coal is about 100 feet below the railroad track, or 630 feet above the tide, thus giving a southward slope along the crest of the axis of 545 feet in this distance of about 25 miles, or a decline of about 22 feet per mile along a line running about south 40° west †.

Anticlinal and Synclinal Axes in Indiana County.

A series of seven anticlinal and six synclinal folds, affecting the bituminous measures of Indiana County, arc described by Mr. W. G. Platt ‡, and may help to throw some further light on the nature and form of these convexities and concavities.

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* It has been impossible for me to reproduce these maps and sections, so I give the references to the original Atlas-sheets of the Second Geological Survey of Pennsylvania.

† Report of Progress in the Beaver-River District of the Bituminous Coalfields of Western Pennsylvania, 1875, by I. C. White, p. 20 Q.

‡ Report of Progress, Indiana County, 1878.

The district is removed from the greatest axes of compression, the folds being described as " broad rock-waves," the crest-lines of which run nearly parallel to each other across the map in a north-east south-west direction through the county. The rocks therefore dip north-west and south-east, except in places where the anticlinals and synclinals *are sufficiently tilted along their central line* to affect the normal incline of the strata *.

One of the features of this series of folds is the Nolo anticlinal, a small subaxis splitting the Ligonier basin lengthwise, on one side of which is the Mechanicsburg and on the other the Centerville synclinals. Both to the south and the north these synclinals become united into one great trough by the disappearance of the anticlinal, and pass under the well-known name of the Ligonier synclinal.

Here we evidently have an elongated convexity in the middle of a larger trough-like concavity.

But the main anticlinals evidently, from the description, are convex along their major axes.

The Indiana anticlinal along the axis from south-west to north-east steadily increases in force and strength, until it lifts the "Elk" or "Boon Mountain," Elk County. In Westmoreland County it is little more than a feeble undulation.

The Chestnut-Ridge anticlinal has an average dip along the strike of the anticlinal between the Conemaugh and Black Lick of a little over 1°, or 100 feet per mile. It appears to have an undulation in the major axis.

The Blairsville Basin is a simple synclinal fold, extending, without structural complication of any kind, from the centre of the Chestnut-Ridge anticlinal on the south-east to the centre of the Indiana anticlinal on the north-west. Towards the north-east, in consequence of the non-parallelism of the two enclosing anticlinals, its width is reduced from seven miles in the Conemaugh to a little over four miles in the latitude of the county-seat. It then expands again to about five miles, at which it continues to and across the Jefferson county line.

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* Ibid. p. 33.

The dips approaching the synclinal from the south-east and north-west are not always of the same force, nor does the axis run along a line midway between the enclosing anticlinals. The synclinal is thrust eastward or westward of the centre of the basin, as the case may be. The floor of the trough has a very gentle but steady slope towards the south-west, a tilt which this synclinal has in common with all similar axes of the county *.

Ligonier Valley.

Mr. J. J. Stevenson, in a general description of the "Anticlinal axes of South-western Pennsylvania," † states that the "Ligonier Valley is a canoe-shaped synclinal pointing out in Preston County of West Virginia, while, south from the gap of Cheat River, another similar synclinal begins, widening and deepening southward. The series of anticlinals described approach each other to the south, so that the consolidation of the axes is so rapid and effectual that at the Parkersburg and Staunton pike, barely 70 miles south from the Pennsylvania line, there remain of all the Pennsylvania axes west from the Alleghenies only those of Laurel and Chestnut ridges, which are reduced in the former case to a simple flattening of the dip, and in the latter to a gentle fold of utterly insignificant proportions" ‡.

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* Report of Progress, Indiana County, 1878, pp. 149–151.

† Report Prog. Fayette and Westmoreland District. Part II. The Ligonier Valley: 1878, p. 268 K K K.

‡ Ibid. p. 270 K K K.

Great Synclinals, enclosing Groups of Sub-anticlinals and Synclinals.

Perhaps the most instructive series of sections of this interesting survey is that across the Panther Creek Basin in Carbon and Schuylkill Counties [*]. With the aid of the underground contour-maps in connection with the sections, this otherwise difficult enclosed series of folds can be readily understood. Commencing with Section No. 1, Sheet No. 1 AA, near the southern termination of the Hell Kitchen Basin [†] (in fact, where it "noses out" in canoe-like form), we find that the Mammoth bed is folded sharply upon itself.

In Section No. 2 the great synclinal trough widens out and deepens, and the Mammoth bed is seen folded into two synclinals, containing subordinate anticlinals, the one to the left (Rhume Run) being overturned. The Rhume-Run overturn continues in Section No. 3. The two synclinals follow on through Sections No. 4 to No. 9, Sheets Nos. 1 and 2, in varying folds, with subfolds that can only be understood by appeal to the sections themselves. Some of these synclinals are tightly compressed, and the overturn of the strata passes to the right-hand side in Sections Nos. 7 and 8.

The contortions of some of the beds on the sides of the synclinals are very curious.

Now the form of this Panther-Creek Basin and subordinate basins cannot be explained by the simple approach of the bounding anticlinals towards each other at the extremities. Every fold, whether convex or concave, "noses out," so that the dip changes at the terminations. The only way in which these boat-like forms can be accounted for satisfactorily is by pressure acting along the major as well as the minor axes, but in a much less degree.

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[*] 'Southern Anthracite Field,' vol. i. A A.

[†] The sections are not reproduced here, but the map is that given in Plate XXXVII. fig. 1, p. 207.

The extraordinary length of the folds of the Appalachians before they gradually die out shows that the dominant pressure acted transversely, but the canoe-like form of the folds when followed out longitudinally, together with the swinging round of the parallel axes which takes place in some districts, point to the action of a force apparently at right angles to the dominating pressure, the resultant folds following the line of least resistance.

Packing of Strata in Synclinals.

Before leaving this interesting field of study, the packing of the strata enclosed in a great synclinal into subordinate anticlinals and synclinals demands notice.

In the first place, the initiation of these subfolds has probably commenced at the same time, or not later than, the larger folds enclosing them.

It seems unlikely that horizontal pressure should push up an anticlinal in the concave bottom of a synclinal, because it is arched or convex to the pressure. When once formed, lateral pressure will go on compressing it.

If, however, we consider all the folds as simultaneously initiated, it is quite conceivable that as the pressure increased the major folds might rise up and enclose the minor. Once enclosed, subsequent squeezing might compress and disturb the minor folds as we see them.

If we examine the geometrical possibility of folding, we shall see that it is possible to arrange the strata in folds at right angles without an actual lengthening of the beds. If the angles of the folds are acute, or less than right angles, it is easy to see that they will not "pack" unless the enclosed beds are squeezed thinner. As we find acute-angled folds in nature, it is evident that some or all of the component beds have been extended along their bedding-planes by squeezing. This is explained in detail in the description of Plate XXXVIII. (Chevron-folds).

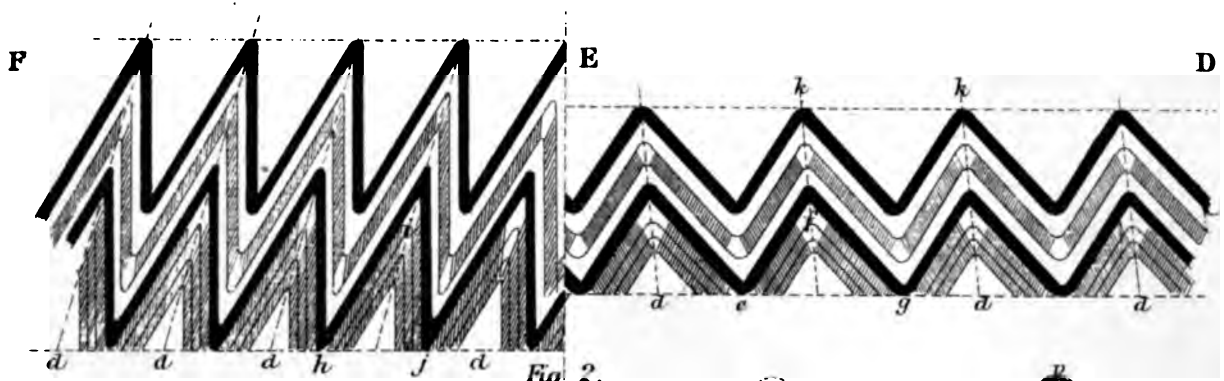

Fig 2.

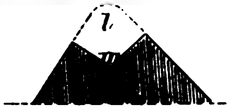

Fig 3.

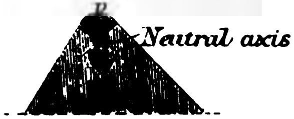

Fig 4.

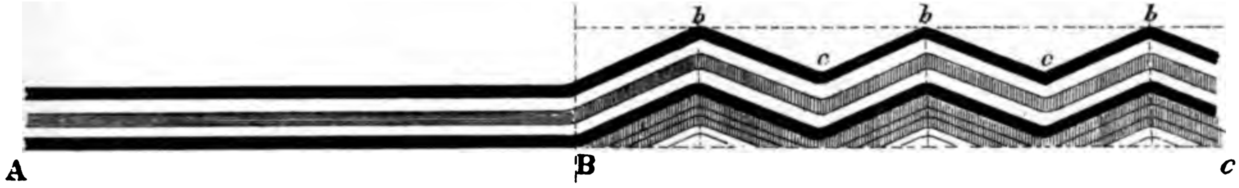

Fig 1.

MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

Sprague & Co Photo-litho London

PLATE XXXVIII.

Diagrammatic Illustrations of the Progress of Folding, and the Extension of Strata that may take place by Lateral Pressure. CHEVRON-FOLDS.

Fig. 1. A to B represents a series of horizontal sedimentary beds, and B to C the same set of beds folded into zigzags, which I call CHEVRON-FOLDS, from their likeness to the Norman ornament of that name. These folds result from the giving way of the beds at the apices, *b b*, and the troughs, *c c*, as if hinged. In nature there are all the intermediate forms between the chevron-folds and the true anticlinal, where the sides are curved. The regularity of the folds is exaggerated in the diagram for geometrical purposes, as will be explained.

Fig. 2. D to E represents the folds further developed, until the two sides are at acute angles to each other. E to F shows them still further squeezed up, until the sides form very acute angles.

For convenience of representation, these folds, which are *unsymmetrical*, having their axes inclined, are shown reversed on each side of the centre line. Their axes consequently incline towards the centre line, as shown in dotted lines.

According to this theory, as each anticlinal rises in gable-form, the core, *d*, is filled with similar folded beds, pushed up from below. Until the folds reach an acute angle, it is probable that the beds remain of their original thickness.

When the beds have turned past a right-angle, extension or lengthening of the beds takes place, as can be geometrically proved in the following manner, and the lengthening of the beds increases as the angle grows more acute.

The angle *e f g* encloses a definite area of matter. If the feet of the triangle *e g* are made to approach each other, one of two things must happen: either the matter must be condensed, or it must flow upwards until it assumes a triangular form having an equal area. Otherwise stated, the area of the triangle remains constant throughout the change of form. *h i j* represents a triangle of equal area to *e f g*, the sides *h i* and *i j* being longer than the sides *e f* and *f g*; consequently the beds forming the sides have been squeezed thinner and lengthened.

It is seen from this example that measuring the length of the beds over the folds in E F, fig. 2 will not give us the original length of the beds. The base-line has been shortened, but the beds have been extended in length and squeezed thinner.

Fig. 3. An enlarged drawing of one of the apices *k k*, fig. 2, showing the cavity *l* which would be left if the bed were turned on its inner edge at *m*.

Fig. 4. The same, showing approximately what takes place in nature in the bending of the beds. O is the neutral axis; *n* is the material which is dispersed by compression; *p* is the tension-space that is filled up from *n* or from the surrounding rocks. (See p. 210.)

CONTORTION IN MESOZOIC AND TERTIARY ROCKS IN BRITAIN.

Athough there are no upheavals in Great Britain of Mesozoic age of sufficient importance to be classified as mountain-ranges, the Mesozoic strata have generally been thrown into anticlinal and synclinal undulations more or less pronounced. As assisting us to understand the movements of rocks on the stupendous scale in which they have taken place in most of the examples already given, a consideration of some of the Mesozoic disturbances may not be uninteresting.

The Yorkshire Geological and Polytechnic Society has published three photographic illustrations of contortions in the chalk of Flamboro' Head. The interest of these excellent examples lies in the circumstance that the chalk of Yorkshire is generally not much disturbed, dipping with tolerable regularity to a point S.E. of its eastern boundary *; yet at Staple Nook, between the Speeton cliffs and the lighthouse at Flamboro' Head, for a space of 300 yards the thin-bedded, hard chalk has been thrown into violent contortions, well exhibited in the photographs referred to. From the base of the cliff to the summit "the chalk is bent, folded, and crushed in every conceivable manner."

This is an illustration on a small scale of what takes place in mountain-ranges, the folding due to the lengthening of the strata being confined to a small area in comparison with the undisturbed portions. The thin beds of chalk are susceptible of bendings and movements upon each other that would not affect more massive beds. Once the strata begin to give at a particular point in this way, other areas are relieved and pushed over towards the line of least resistance.

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* "On the Contortions of the Chalk at Flamborough Head," by J. W. Davis (Proceedings of the Yorkshire Geological and Polytechnic Society, 1885, pp. 43–49).

This is a typical example of the contortions found in Mesozoic rocks in Britain. At Lulworth Cove the Purbeck beds are violently contorted in a somewhat similar local manner.

Mr. Aveline, in the Survey Memoir of the Geology of the Country around Nottingham, says :—"Although the Magnesian Limestone is not much disturbed over this area, either lying flat or dipping at small angles, there are some very sharp anticlinals. One of these has been noticed as bringing up the lower beds of the Magnesian Limestone if not the Coal-Measures, on the west side of Hucknall Torkard. This line of upheaval can be traced from Aldecar Wood, northwest of Linby, to Bulwell, a distance of four miles. Although so sharp that the beds near its centre dip nearly as much as 80°, its influence is not felt for any great distance from the anticlinal axis, for the beds assume their ordinary position in less than 10 yards on either side." *

In the Isle of Wight the Lower Tertiary strata change suddenly from slight inclinations to a sharply turned anticlinal with vertical beds, the chalk having been affected by the same movement †.

Numerous further examples might be added, all of a similar nature; but these are sufficient to show that there is a proportion between the extent and amount of sedimentary beds and the size and importance of the anticlinal movements affecting them.

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* P. 17.

† "The Tertiary Fluvio-marine Formation of the Isle of Wight," by E. Forbes (Memoir of the Geol. Survey, plate 9). Also see Plate accompanying paper "On the Oligocene Strata of the Hampshire Basin" (J. W. Judd, Quart. Journ. Geol. Soc. May 1880).

CHAPTER XVII.

THE CORDILLERAS OF THE WESTERN UNITED STATES.

MESOZOIC AND CAINOZOIC UPTHROWS.

IT will now be profitable to transfer our minds to the Rocky Mountains, and the Green River and Utah Basins. These districts, simpler in some respects than the highly folded Appalachians, are in others more geologically complex. The folds we have been considering are all of one age, whereas, according to the distinguished members of the United States Geological Survey already quoted, the mountains of these Western Territories are of different ages. A later set of mountains, so to speak, has been superimposed upon an earlier.

A reference to the sections accompanying the Geological Surveys of the Fortieth Parallel, some of which are reproduced in this work, will explain this (see Plates X. & XI. pp. 49 and 50). Here we see, in place of the sharp and complicated flexures of the Appalachians, the strata more frequently thrown into long folds, the newest beds, as a rule, being bent into the gentlest curves.

The sections reach from longitude 104 to longitude 120, or over 800 miles. Commencing with the Southern Series (Plate XI. p. 50) in longitude 104 and proceeding westward, we traverse the Cretaceous beds of the great plains horizontal until the Archæan mass of the Colorado Range is reached, where they fold over the flanks in a monoclinal curve, and are underlain by Jurassic and Carboniferous rocks. Between the Archæan mass of the Colorado and the Park Range occurs the

North Park, a basin of Cretaceous rocks, with underlying Jurassic and Carboniferous lying, as before, upon the Archæans. On the western flanks of the Park Range we again come upon the outcrop of the Cretaceous beds, having a gentle anticlinal and synclinal curvature, lying upon the same Palæozoics, but covered with eruptive trachyte and basalt. The series continues westward until the Uinta Mountains are reached, and we pass over the outcrop of Cretaceous, Jurassic, Triassic, and Carboniferous rocks. The Uinta Mountains are composed of a great mass of Upper and Lower Carboniferous rocks, the axis of the range being nearly east and west, or approximately at right angles to the prevailing trend. West of the Uintas we pass over the Wahsatch Mountains, where Cambrian rocks are disclosed. From this point to longitude 120 we meet no more with Cretaceous beds, the older Palæozoics being overlain in places with Tertiary and Quaternary deposits and masses of Rhyolite and other eruptive rocks.

The sections themselves show no strong lines of unconformity excepting between the Archæans and the Sedimentaries that lie upon them.

The Uinta Mountains are, according to Powell, of Cretaceous age, and it is evident that the Cretaceous beds have here overlapped them as well as the Archæans, and that an immense mass of sedimentary beds, estimated by Powell at 30,000 feet, has been denuded from them. The Cretaceous beds must formerly have extended much further west than they do now. There has been enormous denudation of all the area between the Uintas and the 129th meridian.

To what extent Palæozoic mountains existed before the deposition of the Cretaceous rocks upon them it is difficult to say; but it is pretty certain that the Palæozoics have been squeezed up along with the Cretaceous rocks, and have been much further developed in their foldings by the same force that bent the Cretaceous.

The Uinta Mountains are extremely interesting, as showing the hog-back or domed anticlinal on a simple and stupendous scale, and this at right angles to the dominant direction of the other ranges.

Irrespective of the direction of the longer axis, the Uintas are a standing proof that the horizontal pressure accompanying the uplift acted convergingly towards the range. It is also worthy of note that the older and deeper lying rocks have been the most folded.

High Plateaus of Utah.

The High Plateaus of Utah* have been rendered classic ground by the researches of Dutton and Gilbert. The behaviour of the beds is here so entirely dissimilar to those in the contorted regions of the Alleghenies as to have formed the groundwork of special theories of mountain-building.

The sections across the Wahsatch monoclinal to the San Rafael Swell will enable us to understand the characteristics of the structure of this peculiar country.

The general character of this tract of country is that of a platform from 50 to 60 miles wide, bounded on the west by the Wahsatch monoclinal flexure—a grand uplift in which the Tertiary strata, along a base-line of 50 miles, bend upwards in a single sweep diversified by minor irregularities arising partly from minor fractures, partly from erosion, but never of such magnitude as to mask the general plan of the uplift, nor even to greatly interfere with its symmetry. Its eastern boundary is a wall of erosion facing westwards, being the scarped edges of a corresponding but buried monoclinal flexure. The general dip of the strata composing the pleateau is westwards, but an enormous mass of rock has been denuded from the whole area of its summit. The

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* "Geology of the High Plateaus of Utah," p. 160 (U.S. Survey of the Rocky Mountain Region).

Lower Tertiary beds of the western flank are 5500 feet above still more recent ones below, so that the original uplift must have been more than 7000 feet, with a near approach to equality along a line of strike of 50 miles.

The Wahsatch Plateau is a remnant of the original platform on which the Tertiary beds have been preserved; it is a tableland about 6 miles wide. From it we may look down upon the Cretaceous beds, from which about 2000 feet of Tertiaries have been removed. On the eastern border, called the San Rafael Swell, a very low anticlinal roll, a continuation of the more pronounced monoclinal flexure, at least a mile of strata has been removed by denudation.

The formations involved in these great orographic movements are the Carboniferous, Lower and Upper Trias, Jurassic, Cretaceous, Laramie, and Tertiary.

Sheet No. 7 of the Atlas will give us a further conception of the structural peculiarities of the country, but they are to a large extent embodied in the section just described.

The views of Mr. Gilbert and Capt. Dutton are that these gigantic displacements are simple uplifts. The monoclinal flexures are considered to be tension-flexures caused by the stretching of the strata in adapting itself to the greater length caused by the uplifting.

They both point to the faults as being a usual concomitant of the uplifting. Capt. Dutton says there is a strict homology of the faults with the monoclinal flexures, so much so that he considers it preferable to call a monoclinal a "modified fault." The only difference for structural purposes being that in a typical fault the simplest form of shearing is along one plane, while in a monoclinal the shearing lies between two planes.*

Captain Dutton states that the true monoclinal is much more common in the sedimentary than in the volcanic beds.

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* Ibid. p. 26.

He attributes this to lack of flexibility in the latter, which prevents them undergoing differential distortion without fracture. In the sedimentaries the monoclinal is a common form of displacement, though trenchant faults are common enough. In the volcanics there is a tendency to a monoclinal form, but only one example of an unbroken monoclinal.

Mr. G. K. Gilbert * had previously given expression, but in more detail, to somewhat similar views. He says the Colorado plateau is subdivided, in the area examined, by a system of East and West cliffs marking limits of successive strata.

It is further subdivided by longitudinal North and South cliffs produced by faults. These faults are of great longitudinal extent, and of vertical or nearly vertical throw. They are manifested indifferently by fractures and by flexures of the visible strata.

Mr. Gilbert considers we might, *à priori,* assume that the amount of flexure without fracture would depend on the nature of the rock and the rate of the movement.

As a matter of fact, the most perfect arches are found in limestone and very calcareous sandstones, but they are not abruptly bent without partial rupture. Along the margin of the Kaibab plateau, which affords the best examples, the Upper Carboniferous Limestone has a convex curvature of from two to three miles radius.

In the massive sandstones of the Trias he saw but a single instance of anticlinal curvature, at the north end of the Kaibab plateau, and in that the convexity, though sufficient to demonstrate their flexibility, is very slight. In the synclinal curves of the Paria and East Kaibab folds the sandstone is seamed throughout as though it had been crushed and reunited. "That we must regard the phenomena as of slow production, no one can doubt who considers that they include the curvature through an arc of 15 or 20 degrees of a massive sandstone 1000 feet thick" *.

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* The Colorado Plateau System: Geol. Survey west of the 100th Meridian, vol. iii. See also the description of the Water-pocket monoclinal in the 'Geology of the Henry Mountains,' pp. 11-14.

With a large part of this I am prepared to agree, but I would suggest that, in addition to the uplifting, there has been actual compression of the beds themselves. That beds, if sufficiently weighted with overlying strata, may be extended by a force acting from below I have already shown † (p. 168); but I am not prepared to admit that any surface rocks, however plastic, will admit of lengthening by tension to the amount required to produce a monoclinal flexure of a mile vertical. That the whole platform is due to a deep-seated uplifting force acting vertically, so far as the rocks within view are concerned, there can be little question. I am also of opinion that lateral pressure arising from the Earth's crust following a shrinking nucleus, even if we postulated sufficient shrinking, cannot account for the peculiarities of the phenomena. The material composing the platform 50 miles wide and over a mile high—a sectional area of 50 square miles—must be actually forced up from below and remain consolidated to produce this permanent feature of the Earth's surface—permanent until swept away by denudation. The lateral movement necessary to produce the flexures, even acting uniformly upon the whole thickness of the crust, would be insufficient to displace and lift up this enormous mass of material.

If, however, we look at the phenomena in the light of cubical expansion, acting, as I have shown it would, with greater intensity from below, the explanation will I think cover all the described features distinguishing these plateaus.

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* Ibid. pp. 56 & 57.

† Since writing this I am pleased to find that Mr. Gilbert explains the stretching of the sedimentary arches over the laccolites of the Henry Mountains in a precisely similar way.

The Carboniferous limestone rocks are, according to Gilbert, the most perfectly flexed and moulded. They are the lowest and most weighted beds, and would expand the most of any of the series exhibited in the sections. The Triassic sandstones, being higher in the series, would expand less, and the Tertiary rocks at the surface would be unaffected. Consequently the lower rocks, expanding laterally, would be in a state of strain, fitting them to be moulded to the mass of rock forced up vertically from below from great depths. This lateral strain of expansion would grow less and less towards the surface, until the uplift would actually produce a tensile strain, gradually increasing until it reached its maximum at the surface. Capt. Dutton, as quoted, says that the Tertiary (the surface rocks) show little real flexure and much fracture; these fractures he very naturally attributes to the rigid nature of the rock. The rigidity of the rock is no doubt an important element where the lateral pressure is small; Mr. Gilbert points this out in contrasting the greater flexibility of the Cretaceous shales overlying the Triassic sandstones.

If we adopt this, as it seems to me, easy and natural explanation, the upper strata must necessarily be rent by the uplift.

A proportioning of the lateral expansion to the undoubted vertical uplift, due to heating of the mass from below, will also readily account for the flexures running in faults, and *vice versâ,* so graphically described by Mr. Gilbert, the natural flexibility of the rock being one element in the problem.

There is no known case of an anticlinal perfect at its apex that has not originally been deep seated, though it may, by denudation, appear at the surface. The elevation of mountains is a movement so exceedingly slow that their summits get worn away as they rise.

From this cause alone we could hardly expect to behold a perfect anticlinal formed out of surface rocks. There is good reason furthermore to believe that a continuous anticlinal can only be formed out of beds weighted by overlying rocks.

If the theory expounded in this work be founded in nature, surface-rocks must, when the tension exceeds their elastic limit, be rifted by the uprising of the expanding strata from below*. These rifts enable the denuding agencies of chemical action, rain, and frost to act on the rocks with redoubled energy; the area of surface open to attack is vastly increased, and it is further well established by observation that the greatest erosion takes place at the edges of strata. This is, I conceive, the true explanation of the enormous mass of material swept away from the San Rafael Swell and from the platform between it and the Wahsatch plateau. The upper beds have been rifted at the convex bend of the monoclinal, and the strata eaten backwards and westwards into a series of escarpments.

But as to the uplift. Where has all the mass of material forming the plateau, having a sectional area of 50 square miles, come from?

With the rise of the isogeotherm initiated by sedimentation, a cubical expansion of the crust below the plateau has taken place (p. 9).

We have seen that this will give a vertical expansion three times that estimated by Babbage, Lyell, and others for similar cases (p. 114).

The mass of deep-seated expanding rock in a practically plastic condition flowed upwards, its flow being determined by lines of weakness. The monoclinal flexures continuous with strike-faults indicate these lines of weakness; the flexures or fractures, as the case may be, have taken place along the weakest lines, and the whole platform has been pushed up, *en bloc*, between these lines by the expanding matter from below.

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* I find, by experiments on layers of clay divided by cloth, conducted since this was written, that, even where all the layers are equally compressed from the ends, the upper layer of clay is fractured by tension.

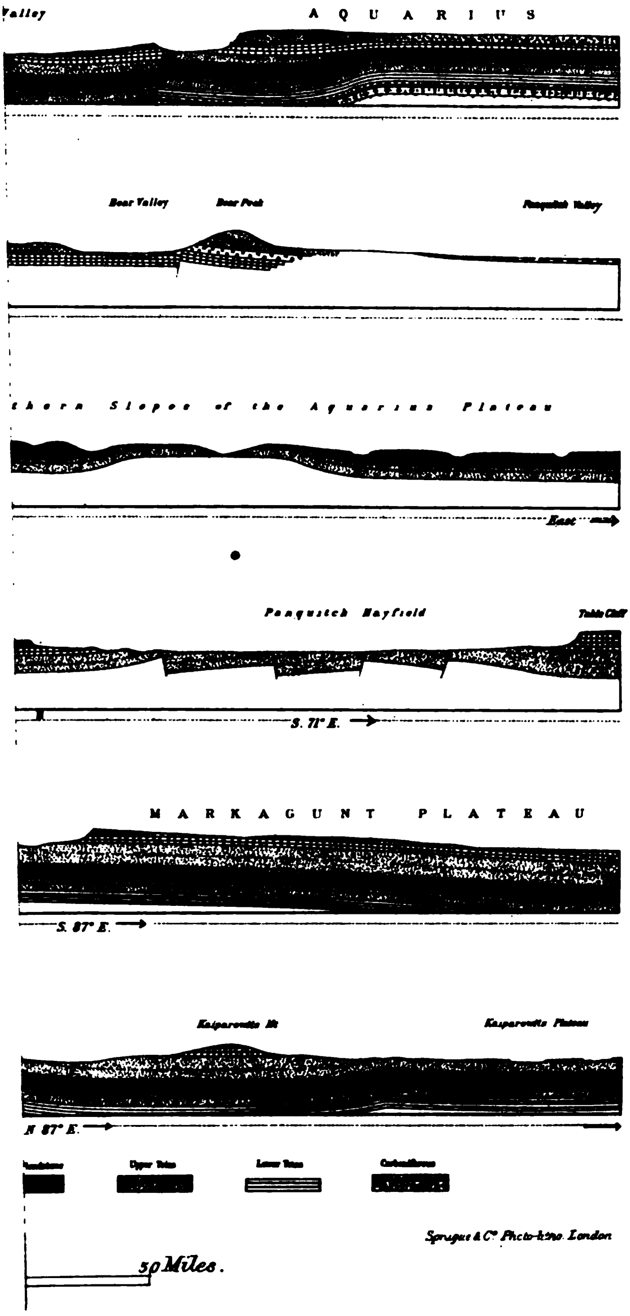
It is quite possible that some of the faulted strips of strata on the monoclinals may be normal or contraction faults, downthrows after the main upheaval has taken place.

Plate XXXIX. is a reproduction of some of the sections accompanying Capt. Dutton's Report on the High Plateaus of Utah, and will serve to make the preceding descriptions intelligible to those who cannot consult the originals.

PLATE XXXIX.

Structure-sections through the High Plateaus, by Capt. C. E. Dutton, U.S.A.—Reproduction of Atlas Sheet No. 7 accompanying the Report on the Geology of the High Plateaus of Utah, 1880: U.S. Geographical and Geological Survey of the Rocky Mountain Region, J. W. Powell in charge.

880. *Plate XXXIX.*



Sprague & Cº Photo-litho. London

The Zuni Uplift.

Not all the flexures of the Plateau region are monoclinal; the Zuni uplift is an anticlinal or elongated quaquaversal. On every side the strata dip away from the axis, and the soft formations that have been eroded from the dome now outcrop in a series of concentric elliptical belts. These formations are the Cretaceous and Triassic. The Carboniferous has yielded less to erosion, and probably forms the whole surface of the northern half of the dome, but at the south it has been broken through and Archæan rocks are actually exposed. As a mountain-range it is 45 miles long, 20 miles broad, and about 3000 feet high. As a geological uplift, it is 70 miles long, 35 miles broad, and 6000 feet high. A rough calculation makes the volume of matter brought by the uplift above the original level surface, 700 cubic miles*.

This range is extremely interesting as showing that the core is of Archæan rocks; not less so is the fact that the south-west side of the anticlinal, which is the steeper, continues as the Nutria monoclinal flexure. May not the foundation rock of the Nutria fold be Archæan also? and, if so, perhaps the same may hold good of the other monoclinal folds. These massive deep-seated rocks must have flowed upwards by circumferential compression, having its greatest intensity deep down in the bowels of the earth. The overlying 35 miles in length of Carboniferous rock, if heated to 600° F., would have a linear expansion of from 580 to 630 feet. The linear expansion on the longer axis of 70 miles would be from 1150 to 1260 feet.

Considered as the arc of a circle, the anticlinal would on its shorter axis exceed its base-line by about 630 feet, but, as the sides are unequal, we may call it 1000 feet.

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* U.S. Geol. Survey West of the 100th Meridian. Vol. iii. The Plateau Region—G. K. Gilbert. Portions of New Mexico and Arizona, p. 564.

Now it is quite evident that the simple expansion by increase of temperature to 600° F. of the rocks occupying the site of the mountain would enable the uplift to be made without fracture. The horizontal expansion of the platform on which it rests may have been relieved by the monoclinal folds.

The upper beds of the elongated quaquaversal, not being expanded, would be fractured; hence the denudation of the crown of the anticlinal, and exposure of the Archæans. In all cases the crown of an anticlinal or the convex bend of a monoclinal would be most subject to fracture. The concave foot of either would, by simple gravitation, be more likely to maintain its continuity.

An appeal to the sections so carefully worked out by the United-States geologists will strongly support this theory. It is quite evident that all such large anticlinals must be filled up by materials of the Earth's crust pushed up from below; and I have shown that it is the result of cubical expansion which will, under given conditions, produce an actual transference of material laterally or from a circumferential boundary inwards.

The form that this flowing will take depends upon a good many factors; and I think we are justified in assuming that true anticlinals, and plateaus bounded by monoclinals, are effects of one and the same cause.

It is quite evident that if the material forming the foundation upon which these platforms rest has been forced into the space by lateral expansion, it will, until removed by denudation, always form a feature of the country, even when the heated masses below cool down. We may establish as a broad generalization that the permanent features of a country are always the result in one form or another of actual transference of material.

The Black Hills of Dakota.

It may be well here to call attention to the very remarkable dome-like uplift called the Black Hills of Dakota. Their position may be seen on reference to the map (Plate X. p. 49). They lie partly in Wyoming, but mostly in Dakota, between the 103rd and 105th meridian W. from Greenwich, and between the 43rd and 45th parallels of north latitude, and they cover an area of about 5000 square miles. Surrounded on all sides by the comparatively unbroken sea of the Great Plains, they are entirely separated from the main chain of the Rocky Mountains, to which system, however, in character and structure they belong. The general geological structure of the Black Hills is as follows:—Around a central area of metamorphic slates and schists containing masses of granite, representatives of the Potsdam, Carboniferous, Trias, Jura, Cretaceous, and Tertiary lie in rudely concentric belts of varying width, dipping on all sides away from the axis of the hills. From the hills outward the inclination of the beds is gradually lost in the rolling configuration of the plains. "At numerous points also within the area of the Hills are centres of volcanic eruption of an age probably coincident with that of the elevation of the mountains themselves" [*].

The geology of the Black Hills is an epitome of that of the Rocky Mountains. The axial core is of Archæan rocks, measuring about 60 miles north and south and 25 miles east and west. It is another great and striking instance, if that be wanted, of elevation by centripetal compression and vertical uplift [†].

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[*] "Report on the Geology of the Black Hills of Dakota," by H. Newton and W. P. Jenney, U.S. Geogr. and Geological Survey of the Rocky Mountain Region, 1880, p. 39.

[†] In England, on a smaller scale, we have similar representations of the simple type of domical uplift. One of the most striking of these is the Woolhope dome. As first pointed out by Sir Roderick Murchison,

The Henry Mountains.

It may not be out of place here to consider a peculiar type of mountain-structure which Mr. Gilbert has the merit of investigating and satisfactorily explaining.

The Henry Mountains, unlike mountain-ranges, are individual dome-shaped mountains rising out of an elevated plateau. They are situated in Southern Utah in the meridian of 110° 45′ and the 38th parallel. Fifteen miles to the west, and roughly parallel with a line drawn through the group, is the Water-pocket fold or monoclinal.

They cannot be said to have a trend, being a group of five individual mountains. The highest rise about 5000 feet above the plateau at their base, and 11,000 feet above the ocean-level.

Mr. Gilbert shows very clearly that each mountain is a dome of strata arched up by the intrusion of a mass of porphyritic trachyte. This intrusion began by a creeping of the igneous matter along bedding-planes and a rising up or tumescence by constant accession of molten rock from below. These massive dome-like cores Mr. Gilbert has named "laccolites" (stone cisterns).

There are in the Henry Mountains vertically two zones of

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the Woolhope district (Upper Silurian) is formed of two concentric narrow ranges of hills, almost continuously enveloping a broad, almost ellipsoidal or, rather, pear-shaped dome. The longer axis is 10½ miles, the transverse 4½ miles. The axis of figure of the district is N.N.W. and S.S.E., which in the southern part is coincident with the axis of elevation, but in the north the axis of elevation is near the western border; in consequence of this the dips are very rapid towards the west. The axis thus crosses at an angle of about 75° the general trend of the Silurian flexures throughout Britain, and is a striking proof of the centripetal character of the elevatory forces. The central dome is laid bare by denudation, and is about 684 feet above O.D., the exterior circle of hills ranging from 700 to 900 feet.—See "The Malvern Hills" &c., by John Phillips (Mem. Geol. Surv. vol. ii. part 1, p. 166).

occurrence of laccolites. Some laccolites have intruded themselves between Cretaceous strata, others between Jura-Triassic, and others between Carboniferous; from the highest to the lowest the vertical range is not less than 4000 feet. Mr. Gilbert considers that he has established a relation between the specific gravity of the laccolite and the level or zone at which it was intruded. Want of space prevents me going into much further detail. For a study of these singularly interesting mountains, I must refer my readers to the memoir.* There are, however, one or two points I would dwell upon which will help to further elucidate some of the physical principles involved in mountain-building. It affords me satisfaction to find that Mr. Gilbert here accounts for the extension of the strata over the dome by *compressive extension*, in a manner almost identical with that put forth in this work to explain the lengthening of the folded beds which has taken place in some mountain districts through the protrusion of Archæan masses into overlying sedimentary beds † (p. 168).

The intrusion of these immense cisterns of molten rock must have communicated a considerable amount of heat to the overlying sedimentaries.

I would add to Mr. Gilbert's theory the horizontal radial expansion of the overlying rocks produced by this injection of heated matter. The superincumbent beds or shells would be assisted in adapting themselves to the growing tumescent mass below by their own expansion. Describing the Lesser Holmes arch ‡, he says the major part of its surface is composed of one bed, the Vermilion Cliff sandstone, broken only by erosion. "Comparing the length of this bed in its present curved form with the space it must have occupied before it was upbent, I find that in a distance of 3 miles it has been elongated 300 feet." A rise of 1000° in temperature would expand a sandstone about 90 feet in 3 miles. From this we may see that the expansion of the bed and the tendency to arch up will help to initiate the dome-like form.

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* 'Geology of the Henry Mountains,' p. 82.

† These mechanically identical views have been independently arrived at, as my explanations were penned before reading Mr. Gilbert's exposition.

‡ Ibid. p. 81.

A continual accession of heat from below, by the molten rock rising through a pipe in the centre of the laccolite, will intensify the tendency.

Variations of temperature during the process of filling, and the increment of expansion at each change, might also add to the efficiency of the expanding force.

We cannot, however, assume that a bed, the summit-curve of which is destroyed by erosion, was formerly perfectly continuous unless we have other evidence. There is no doubt in my mind that the upper beds must have been rifted from the surface down to the zone of *compressive extension.* The depth of the rocks into or under which the laccolites have been intruded is given by Mr. Gilbert as Cretaceous 3500 feet, Jura-Trias 2930 feet (pp. 4–6)*.

Mr. W. G. Collingwood, in his 'Limestone Alps of Savoy,' published as the first supplement of Mr. John Ruskin's 'Deucalion,' expresses the opinion, from careful personal study, that many of the anticlinal bends of the Alps have been broken at the apex (p. 129). There is much freshness in this interesting work, the author, with an artist's eye for form, readily grasping the complex structure of the Alps and representing the extraordinary foldings with a firm and flowing hand. There are various ways of looking at nature, and geologists should not neglect the artistic, which I may add they are apt to do.

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* See "Miniature Domes in Sand," Geol. Mag. Jan. 7, 1884, p. 20, an analogous phenomenon produced by air in wet sand.

CHAPTER XVIII.

FAULTS OF THE PLATEAU SYSTEM AND THE GREAT BASIN.

Both Mr. Gilbert and Captain Dutton are of opinion that the faults occurring along the monoclinal flexures are a continuation of these uplifts and due to the same force that has raised the plateaus.

Captain Dutton, however, guardedly adds that it is impossible to tell whether a fault is due to an uplift or a downthrow[*].

Doubtless this, in the present state of our knowledge, is true of most faults, though if the general considerations laid before the reader in this work are of the value I attach to them, normal faults are in most cases due to downthrows.

If, in tracing a fault through nearly horizontal strata, we find that the rocks at one side of the fault traced from the extremities sag in the centre, we may, I think, reasonably attribute the fault to a downthrow. If, on the contrary, one side remains horizontal and the other arches up from the extremities along the fault-line to the centre, we may consider it an upthrow. If one side is convex along the line of fault and the other concave, there probably has been an uplift at one side, and a downthrow at the other.

A little east of the centre of the (Aquarius) plateau, a fault throws down the plateau west of it from 600 to 1000 feet.

"This movement has produced a sag in the central part of the plateau, but the altitude of the summit is nearly all regained towards the west by a gradual ascent." * "This fault is comparatively recent for the most part, and is probably coeval with the other great displacements of the Pliocene Quaternary system."

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[*] 'High Plateaus of Utah,' p. 25.

The East Musinia fault Capt. Dutton does not include among the greater displacements, though its length is probably 45 miles; and at one place in Gunnison Valley the shear reaches more than 2000, and possibly near to 3000 feet. It is parallel to the northern portion of the Thousand-Lake fault, and the two hold between them the sunken block of Gunnison Valley, and the continuation of that block obliquely across the great Wahsatch monoclinal. "It appears to be a very clear case of a *block dropping through the drawing apart of the strata, and sinking to fill the gap thus produced*. Another instance occurs along the western base of the Aquarius Plateau in the southernmost part of the Grass Valley. Here the block between the faults, instead of shearing sharply on both sides, has partly careened and settled down synclinally" †.

The Sevier fault is an interesting instance of the greater displacements. It makes its first appearance at "Pipe Spring," at the base of the Vermilion Cliffs, and presents a remarkable attitude. Approaching it from the west, the beds are turned down on the thrown (downthrow) side, and remain horizontal on the other. The beds 5 miles from the fault on the thrown side come back to horizontality at about the same levels which they occupy on the other side of the fault. Passing on to the base of the Paunságunt at Upper Kanab the beds on the thrown side are flexed upwards, while on the lifted side (east) they are horizontal. Further on the fault is stepped and here and there somewhat comminuted, but with one predominant shear, forming the western wall of the Paunságunt Plateau.

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* 'High Plateaus of Utah,' p. 293.

† Ibid. p. 34.

From Hillsdale for 10 miles the throw is about 800 feet, and then increases slowly but steadily for the next 60 miles. Along the east side of the Panquitch Valley it is very difficult to study, because it cuts the volcanic rocks, which are much confused, and here is one of the great eruptive centres. At East Fork Cañon the thrown beds, consisting of volcanic conglomerate, are turned up monoclinally, but are sundered by the fault at the summit with a shear of 3000 feet.

The maximum displacement is apparently attained a few miles south of the Mormon village of Monroe, and from that point northward it rather rapidly diminishes. Between Glenwood and Salina the apparent shear has become zero. But the circumstances are remarkable. The fault from Monroe northward is a secondary displacement superposed upon an older one. The zero point of the fault is quickly succeeded in the same line by a resumption of the shear, but in the opposite direction; *i. e.* the throw north of the zero point is to the east, while south of this point it is to the west. The fault with its throw reversed now continues northward, crossing the lower end of San Pete Valley, and becomes the eastern wall of the San Pete Plateau, its shear increasing until it reaches nearly to Mount Nebo. The length of the displacement, so far as known, is nearly 220 miles.

This fault forms the western fronts of the Paunságunt and Sevier Plateaus, and the eastern front of the San Pete Plateau, and is probably a displacement due to uplift.

The Hurricane fault is a great displacement, probably over 200 miles, and it nowhere appears to take on the true monoclinal form. Its maximum throw is near Cedar on the western flank of the Markágunt, where it reaches on an average along 20 miles of its course about 5000 feet.

From the Grand Cañon northwards for 40 miles it is nearly a simple fault, though in some places it shows comminution of the rocks in the vicinity of the fault plane, and in a few places the beds on the thrown side are turned up. Along the south-western base of the Markágunt the upper beds on the lifted side of the fault have been eroded backwards, and the lower beds have in several places been turned up with a sharp flexure and stand nearly vertical; in one instance they have been turned past the vertical. This movement seems to be exceptional, no other instance of the same kind having been seen elsewhere. The Carboniferous has been brought up by it so as to abut against the Tertiary on the thrown side of the fault, and right at the plane of shearing the displacement of the lower beds seems to be about 12,000 to 13,000 feet. But away from the fault plane the beds quickly come back to their normal position, with an uplift of about 4000 feet *. The sharp upward flexure of the lower beds can, it appears to me, be best explained on the supposition that flexures have been produced in the lower beds on a minor scale, by a pressure insufficient to develop them at the surface. The contortions have been brought to view by the uplift or downthrow, whichever it may have been.

It is almost impossible, from the information at hand, to determine which of the faults are contraction and which expansion faults. When we consider the enormous vigour of the volcanic action which has taken place in Tertiary time continuing into the Quaternary, we may well assume that the isogeothermals during that time rose so as to affect an enormous thickness of the Earth's crust. The consequent cubical expansion has provided the material for building up this plateau system; but the isogeotherms must have since sunk and be still sinking; consequently, though the relative levels of the plateaus and the country on which they are based may be permanent, contraction must have set in, followed by differential subsidence.

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* 'High Plateaus of Utah,' p. 29.

A study of Atlas sheet No. 7*, giving sections across several of the plateaus, inclines me to consider the faults as there represented, actual downthrows to the west; if this be so, they are normal or contraction faults. (See Plate XXXIX. p. 228.)

Faulting in the Great Basin.

Mr. Israel C. Russell has lately described the system of faults found in the Great Basin †, which will, I think, help us much in understanding faulting. The fracturing has affected the whole great area between the Sierra Nevada and the Wahsatch mountain-systems. The general trend is approximately parallel to the enclosing mountain-ranges, or north-north-east. The orographic blocks are long and narrow, sometimes in the ratio of 50 to 1 or even more.

The average elevation of the area of displacement is about 4000 feet above the sea, and from 3000 to 5000 feet below the enclosing mountain-ranges.

The faults have fractured volcanic, metamorphic, and sedimentary beds alike, and have increased their displacement during the last few years. These orographic movements are still in progress throughout the Great Basin.

The trend of the faults is nearly always to the thrown side and is usually steep, an inclination of 40° to 70° with a horizontal plane being most common. They are irregular with reference to both horizontal and vertical planes, and are frequently curved; where the larger faults branch, the branches are usually on the thrown side. *"The tilted blocks occupy more horizontal space than they did before the faulting took place."* ‡

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* Geology of the High Plateaus of Utah.

† "A Geological Reconnaissance in Southern Oregon." Fourth Annual Report of the U.S. Geological Survey, 1882-83.

‡ P. 452.

The displacement, so far as present observations extend, is by simple faulting, never by flexing.

The present topography of the Great Basin has been imposed upon a far older structure, in which plication was one of the principal elements.

Mr. Russell is clearly of opinion that these faults are due to downthrows, not uplifts. Though I cannot agree with his view that the movements are in any way related to the "tangential strain acting on the borders of the Great Basin, while the interior region subsided," I fully accept his opinion that the faults are downthrow faults. According to my view, no downthrows could take place while a region was subjected to great compressive strain. It is when these have ceased and contraction has set in that blocks of the strata subside (see Chap. VIII.). The strata could only be extended in a horizontal line in the way these are extended, either by the wedge-like blocks of strata forcing out the buttressing portion of the crust on either side, which is improbable, or by contraction opening a gap into which the blocks may adjust themselves, in contact, by subsidence.

An apparent extension might take place when the area affected by faulting really contracts.

If the blocks have varying inclinations or hades in the fault planes they will, on contraction, subside so as to still seal up the openings and leave no fissures; they would in this way appear to have extended to fill up a larger space, whereas they have really contracted and settled down in a wedge-like form to fill up the *same* space.

That faulting having a considerable inclination to the downthrow could take place by "lifting" seems to me highly improbable.

Consider what it means:—

Let A B (Plate XLII. fig. 3, end of book) represent faulted strata, C being the downthrown side and *e f* the inclined throw. It follows, if produced by uplift, that the strata on either side must be compressed to the extent of the horizontal distance *g h*.

To produce this compression we have the wedge-like action of the block D against the block C.

Those who hold this view, and it has been well explained by Jukes ('Manual of Geology,' p. 233, 1859), maintain that it is the superior area of the base of the block D that enables an uplifting force to affect it more than the block C. I contend, on the contrary, that the two blocks with such an inclined fracture would be nearly equally affected; that it would be easier to lift C *pari passu* with D, though the area of the base be smaller, than to produce the necessary amount of compression which the greater uplifting of D would demand, even if the fault were in existence.

When we appeal to nature we find that there are, excepting occasionally in the immediate vicinity of a fault, no signs of any such compression in connection with a system of faulting where the hade is towards the downthrow.

If we accept the proposition that uplifts, plications, and reversed faults are due to expansion caused by a local accession of heat to the part of the Earth's crust so affected, it follows naturally that on a dissipation of that heat the strata must readjust themselves to meet the diminution which takes place, not only on horizontal planes, but in the foundation in bulk. Here lies the true explanation, which readily and naturally explains the subsidence of the block with the lesser base, together with the step-faulting that often follows the subsidence. I have indeed some doubts whether step-faults are *ever* produced by uplifts. (See Plate XV. p. 101, and Plate XVI. p. 106.)

CHAPTER XIX.

UINTA MOUNTAINS.

THESE mountains are remarkably interesting as exhibiting a simple and original type of structure. Prof. J. W. Powell, in his instructive "Report on the Geology of the Eastern portion of the Uinta Mountains,"* goes very fully into the various types of mountain-structure, classing the Uinta Mountains as a "Primary topographic form."

It is a form intermediate between the true anticlinal and the monoclinal plateau, that is a "Plateau with rounded summit and abrupt shoulders on the flanks."†

We may therefore look upon the Uinta type as a flat arch springing from monoclinal flexures.

One of the remarkable features of this range, before pointed out, is the direction of the axis, which is east and west, or at right angles to the general trend of the ranges of the Western Territories.

It is over 150 miles long and is 50 miles wide. The axis is not a straight but a sinuous line. From the axis on either side the beds are flexed in a gentle curve to the north and south for many miles, until the flanks of the range are reached, where the beds are seen to drop down by abrupt flexures or faults, and these lines of maximum displacement are subparallel with the axis. In some places this block was severed from the adjacent country by fracture; in others by more or less abrupt flexure, and it was itself flexed gently from the axis on either side *.

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* U.S. Geological and Geographical Survey of the Territories, 1876.

† Ibid. p. 21.

Prof. Powell estimates that its axis has been lifted above the level of the adjacent country about twenty-five thousand feet, or thirty thousand above the sea. On the north side, on the line of greatest flexure, is a fault in one place having an estimated throw of twenty thousand feet. On the south side the line of greatest flexure is very irregular, being complicated in some places by faults having uplifts opposed to the downthrow of the flexure. On either side the great displacement is partly by faulting, partly by flexing, and either flank is a zone of diverse displacement, where the strata are faulted, flexed, twisted, and contorted in many ways †.

Taking the area of the eastern portion of the Uinta Mountains (represented on Plate 2 in the accompanying Atlas) at 2000 square miles, there has been about 7100 cubic miles of rock removed by denudation, or about a mean of 3½ cubic miles to every square mile of surface ‡.

One of the most remarkable facts connected with this range is the extraordinary planing down which it has undergone, though the uplift began as late as Cretaceous times. So much so is this the case that the Green River cuts into it transversely from the north, then swerves to the east, following the axial line along Brown's Park, then turning south and again flowing westward over the Yampa Plateau, and thence over the Eocene beds southwards. The Eastern end of the Uintas has an irregular *quaquaversal* dip, being complicated by the folds of the Yámpa plateau. At the extreme eastern end is Junction Mountain, a small anticlinal with a north and south axis. The western end of the range terminates against the Wahsatch Mountains.

Prof. Powell looks upon the whole range as a direct uplift, and considers the faults as flexures broken during the lifting.

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* *Loc. cit.* p. 177.

† P. 12.

‡ P. 181.

There seem very strong reasons for this view, but to my mind not entirely conclusive ones. The explanations leave lateral pressure entirely out of account. After a careful study of the excellent sections and maps, and the extremely lucid and systematic explanation, it appears to me that lateral pressure has *accompanied* the uplifting. It is otherwise difficult to explain the anticlinal and synclinal flexures, and especially those of the Yampa Plateau. Nor does it seem probable that the main range is due alone to simple distension, which would be the case were it an uplift only.

Again, Junction-Mountain anticlinal points to lateral compression, acting in the direction of the main axis of the Uintas.

I feel very great diffidence in suggesting an explanation in some respects different to that adopted by Prof. Powell, who has studied the structure so carefully on the spot, as in the main I cordially agree with his views. Still the suggestions of a mind coming fresh to a consideration of the subject may have some value.

The displacement in *mass* is doubtless mainly due to a deep-seated force affecting the underlying rocks as an uplift.

According to Powell the movement commenced at the close of the Point of Rocks period * (Cretaceous period); since then there has been a great deposit of Tertiaries in the surrounding region, and it is inferred that the Bitter Creek group represents the old shore-line established by the upheaval of the Uinta Mountains †.

Eastward from the Green River the beds of this group rapidly thicken out until at Richard's Peak they reach over 5000 feet, with a great development of conglomerate at the base. Richard's Peak itself is a monoclinal ridge of this conglomerate.

If this be a true history of the structural geology of the

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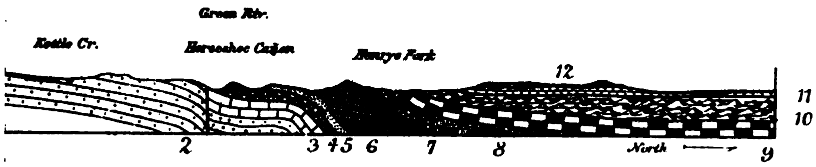
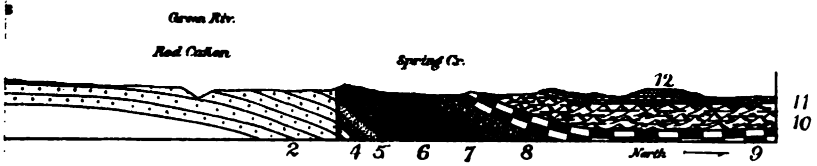
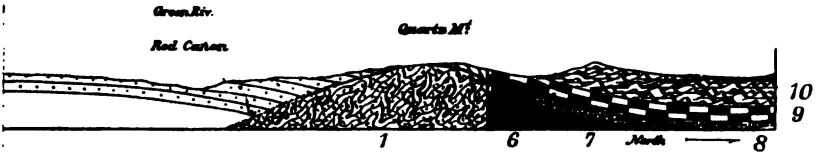
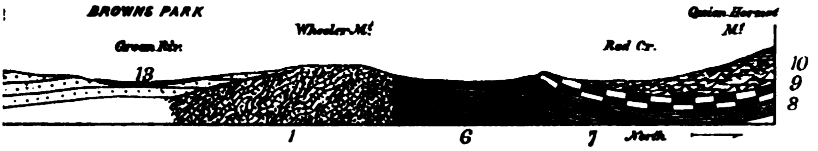
* *Loc. cit.* p. 173.

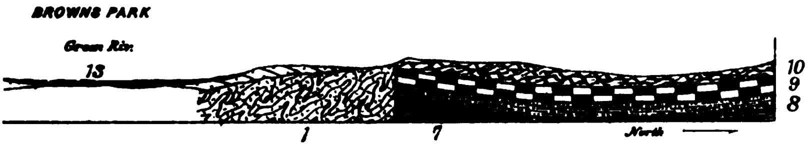
† P. 162.

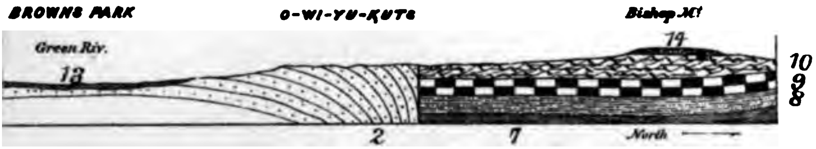












20 Miles

Sprague & Co. Photo-litho London

PLATE XL.

Structure section through the Uinta Mountains, reproduced from Plate 1., Atlas Sheet accompanying the "Report on the Geology of the Eastern portion of the Uinta Mountains," by Prof. J. W. Powell, U.S. Geological and Geographical Survey of the Territories, 1876. The groups are numbered in ascending order.

PALÆOZOIC
1. Red Creek Quartzite.
2. Uinta Group.
3. Red Wall and Lodore Groups.
4. Lower Aubrey Group.
5. Upper Aubrey Group.

MESOZOIC
6. Flaming Gorge White Cliff, Vermilion Cliff, and Shinarump Groups.
7. Sulphur Creek and Henry's Fork Groups.
8. Salt-wells group.
9. Point of Rocks group.

CAINOZOIC
10. Bitter Creek group.
11. Lower Green River group.
12. Bridger and Upper Green River groups.
13. Brown's Park group.
14. Bishop Mountain group.

The planes of sections are parallel and equidistant, 6 miles apart. The base lines represent the level of the sea. The length of each section is 57 miles; the vertical and horizontal scales being the same.

The formations in the region of country embraced in the map accompanying the report have an aggregate thickness of 50,000 ft. (Preface to Report, p. iii.)

district, it is evident that the degradation of this enormous uplift went on throughout *pari passu* with the upheaval. There were therefore two agencies at work tending to reduce the enormous difference of level which otherwise would have occurred between the mountain and its platform, —denudation of the mountain, and the filling up of the area around it with the deposit therefrom. No explanation which does not take account of the passage of the Green River across the range as before described, can be fully satisfactory, for as the inception of the uplift began so late as the Cretaceous, ending with a total rise of 25,000 feet above the surrounding country, the river must be of later age than the mountain, for it is evident it could not begin to flow across it from the surrounding sea. The valley of the Green River in Brown's Park, eroded out of the Uinta sandstone, is at a lower level than the Tertiary deposits flanking the downthrow to the northward. It is quite likely that the whole platform has been formerly at a higher level more favourable to rapid erosion. The axis of the anticlinal being ruptured in the upper beds by the uplift (see Plate XXIII. fig. 2, p. 173), the drainage of the interior region of the mountain has partly followed that line, lowering it rapidly into a gorge-like valley, which in time, as the base-level of erosion was reached, became wider. The form of the valley, situated as it is on the axis of upheaval, leads me to doubt if the upthrow was principally effected by faulting. We should hardly expect to find the axis of upheaval or apex of the curved strata so near a fault, if the fault were a shear caused by the same movement. Still less should we expect the line of erosion to follow so near this fault cliff. The very rapid curvature downwards of the Uinta sandstone, shown in section 8 (Plate XL. p. 245) at O-wi-yu-kuts, favours the idea that there has been rapid flexure where the fault now exists; and I would suggest whether another reading of the sections might not give us a flexure approaching the vertical, like that shown near Henry's Fork on section 3, and the Yampa Plateau, section 8. The denudation of this flexure, and superimposed faulting, would thus account for the total uplift without resorting to a shear of 20,000 feet.

The fault at the north side of the Yampa Plateau (section 8) is evidently to my mind an actual downthrow to the north, giving a general tilt to the mass of the Uintas southwards. By analogy of the usual succession of such faults, we may look upon the fault on the northern boundary of the Uintas as also a real downthrow of the strata on the north side. This fault is shown in sections 7 and 8 (Plate XL.), and more decidedly in Section 9 of Atlas Sheet, plate 1, as shearing the Bitter Creek group (Tertiary beds) immediately overlying the Point of Rocks group, although the former are assumed to have been laid down after the uplifting began. It seems to me more consistent with the facts, as represented, to look upon this fault as a downthrow along the line of weakness caused by the previous uplift flexure.

The re-deposition of the matter degraded from the Uintas would aid the downthrow, while at the same time tending to keep up the general level of the country. Since then the whole country to the north has increased in elevation, suffering in its turn elevation after deposit.

It is possible that there may even have been, to some extent, an after uplift of the newer strata to the north, along the line of the old fault. In this way we may account for the Green River having worked its way back through the Uinta uplift until it received the drainage of the newer territory beyond to the northwards. The history of the Uinta uplift is one of very great interest, and I offer the foregoing merely as a tentative explanation.

CHAPTER XX.

VOLCANISM IN THE HIGH PLATEAUS.

THE Plateau province has been the scene of volcanic activity from the middle of the Eocene to almost the present time. Between the commencement and cessation of that activity the eruptions have been intermittent. There have been long periods of repose, during which the subterranean forces were only gathering strength and material for fresh outbreaks.

The oldest rocks having an irruptive origin are tufas. They are in this district stratified water-laid rocks of arenaceous texture, sometimes marly or even shaly; their materials being derived almost entirely from the decay of lavas. Whether the lava-sheets, which by their decay yielded the clastic materials for these rocks, remain buried beneath the later immense outpourings, or have been wholly dissipated, it is impossible to say. The tufas must be referred to the latter part of the Eocene.

The oldest massive rocks of volcanic origin are only found in a few places where faulting or great erosion has taken place. These propylitic masses have been much degraded by erosion before being covered by the later andesites. Two exposures—one situated in the grand gorge of the Fish-Lake Plateau, and the other in the deepest ravines of the Awapa, near the Aquarius—have disclosed them beneath nearly 3000 feet of trachytes.

The hornblendic andesites succeeded the propylites, with apparently a long interval between them. They were erupted from the same localities, or from vents in the immediate vicinity. The mass of these rocks now exposed is greater than that of the propylites, and the lavas are considerably more varied in texture and appearance.

The real magnitude of the andesitic extravasations is shown by the great bulk of the conglomerate derived from their ruins.

The third epoch of activity was by far the grandest of all, and is marked by the extravasation of trachytic masses alternating with augitic andesites and dolorites. A long interval separated these eruptions from the previous andesitic outbreaks, for the andesitic rocks were extremely degraded by erosion, and the conglomerates formed before the earliest outpours of true trachyte.

The area of activity was greatly extended in the trachytic age; new volcanoes opened and poured forth immense floods, which became so vast as to overwhelm the greater part of the district, generating a new topography.

The basalts, the youngest of the eruptive rocks, in their localities of eruption show a tendency to abandon those parts of the district which had been seats of the grander and earlier periods. A large number of basaltic streams have emanated from the walls of the plateaus.

In the western wall of the Paúnságunt this is the case. In the great majority of cases the vents stand near faults, but, curiously enough, mostly break forth on the lifted side, and very rarely on the thrown side of the fault *.

Capt. Dutton, from his extensive study of the volcanic phenomena of this region, arrives at this conclusion :—*Volcanic phenomena are brought about by a local increase of temperature within certain subterranean horizons.*

There are, according to Capt. Dutton, two systems of displacement, the earlier occupying an interval of time between the Mesozoic and the Tertiary *. These consist of a series of monoclinal flexures, each perfect in form, which trend from north-west to north-north-west. They involve the Mesozoic beds, but not the Tertiary. They come up from the south-east, and disappear under the Aquarius Plateau, and on the southern and south-eastern flanks are laid bare by a vast erosion.

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* 'High Plateaus of Utah,' pp. 55–62.

The Echo-Cliff flexure, the Water-Pocket flexure, one of the grandest monoclinals of the west, and the San Rafael flexure, all monoclinal flexures of imposing dimensions and perfect form, Capt. Dutton considers go far back in Tertiary time, and possibly are pre-Tertiary. Mr. Gilbert believes the Water-Pocket flexure belongs to the interval that separates Tertiary from Cretaceous time. The Echo-Cliff flexure is probably much younger. None of them appear to have any sympathy with the Pliocene-Quaternary faults of the High Plateaus †.

The great displacements represented by the main flexures and faults bounding the High Plateaus Capt. Dutton places about the middle of the Pliocene, judging from the small amount of erosion to which their displaced edges have been subject.

But, while comparatively recent, some are older than others. The two Kaibab faults seem to have undergone part of their shearing before the principal epoch of displacement.

The Sevier fault shows signs of two epochs of activity in some portions of its extent.

Between Monroe and Gunnison the flexure is clearly older than the fault that cuts it.

The Musinia faults cut obliquely across the great monoclinal of the Wahsatch Plateau, and show little sympathy with it.

The Paunságunt fault, meeting with the northern extension

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* Ibid. p. 44.

† Ibid. p. 45.

of the East Kaibab flexure, is plainly independent of it, and is decidedly younger. Capt. Dutton remarks it as a curious circumstance that where we find this two-period displacement the motion of the fault is often reversed, the lift of the first period is the throw of the second. He believes this to be true of the majority of the cases where the double movement has been detected.

This last information is of a most interesting nature, and strongly tends to confirm the views set forth in this work. When, as we find, there have been three periods of activity and three of rest, it must be very difficult to assign to each its particular effects of displacement—one displacement being superimposed upon another.

Compression flexures initiated in one period may be increased in another. Contraction-faults of one period may be crushed up by the expansion of the rocks during the next reign of volcanic activity. When we find that the latest and greatest movements, those that can be most easily studied, show during the active volcanic period great flexing and uplifts, it is what our theory would predicate. When we find that the faults imposed on these previous flexures show downthrows where there had before been uplifts, we say that this also is in accordance with the theory enunciated, and that they are due to contraction.

I have given perhaps an undue space to the discussion of the problems pointed out by the Plateau-system. It is, however, here that we see the latest phases of mountain-building—so late that its effects are not obscured by wide-spread waste.

That the faults of a mountain-system are, as a rule, later than the flexures which accompanied the mountain-building I hope to establish as a wide generalization; the fact is much more patent in the older systems than in this.

We thus have impressed upon us the conviction that a great mountain-system is not the result of one continuous action, but of successive efforts, in each of which efforts there is an elevation accompanied by more or less lateral compression and an after-faulting and subsidence. The uplift, as well as the subsidence, is differential, and, together with denudation, serve to model the ground. On the whole, the uplift is considerably in excess of the subsidence within the immediate area of the range. This is due to permanent displacement of material from under the surrounding areas deep down in the Earth's crust. In the areas from under which the materials were laterally extended by expansion, the subsidence will eventually be in excess of the uplift. But this is a point that needs further investigation.

Note.—Prof. Joseph Le Conte, in a most interesting paper entitled "A Post-Tertiary Elevation of the Sierra Nevada shown by the River Beds," published in the September number of the 'American Journal of Science' (1886), appears to have arrived at somewhat similar views to those enunciated in this chapter; he says (p. 178):—"But after the crust has again become rigid, bodily movements of a somewhat different kind, and the cause of which we still very imperfectly understand, give rise to fractures which by *gravitative settling* produce *normal* faults so common everywhere. It is certain that the great normal faults which characterize the Basin region, among which must be counted the Eastern Sierra fault and the Western Wahsatch fault, were produced in this way long after the orogenic crumpling had ceased. It is certain, also, that the prodigious faults which characterize the Plateau region, where there was no orogenic crumpling at all, were formed in the same way."

CHAPTER XXI.

THE CONNECTION OF VOLCANIC ACTION WITH MOUNTAIN-BUILDING.

VOLCANIC phenomena have received very early attention from geologists. The effects are so striking, so fraught with interest and danger, as readily to seize upon the imagination. Although there had been, from Spallanzani in 1788 to Scrope in 1825, many illustrious observers of volcanic phenomena, the latter geologist was the first to frame a systematic theory of volcanic action. Since then there have been many investigators, and Prof. Judd of late years has added much to our knowledge of the subject[*].

The connection of volcanic action with mountain-building has not, however, received so much consideration as the structure of volcanic cones, the mode in which they are built up, their intermittent activity, and the causes which have given them birth.

In saying this I am not losing sight of the enormous amount of work which has been done by geologists in mapping ancient lava-flows, or the discovery and masterly investigations by Prof. Judd of the basal wrecks of the volcanic cones of the Hebrides. Nor am I insensible to the valuable and still earlier work of Ramsay and Jukes in the Snowdonian range, nor to the complete and magnificent way in which the relative ages of the interbedded volcanic rocks of this complicated region were worked out by them.

To enumerate all the workers in this branch of Geology would be but to give a list of the most distinguished geologists of the latter half of the century.

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[*] "Contributions to the Study of Volcanoes," Geol. Mag.; 'Volcanoes.'

That volcanic action was energetic at the commencement of the so-called "periods" into which, for purposes of classification, it has been necessary to divide the geological history of the Earth, has been noted by many, and especially by Prof. Judd.

It has also been observed that volcanic action has ever been present during the building of mountain-ranges. In the earlier days of geological science the general connection between volcanicity and the upheaval of mountains was seen, and was looked upon as cause and effect. The keen eye of Hutton early discovered the general connection between the two phenomena. The leading idea underlying his theory of the Earth appears to be that of an uplifting of the strata by heat and volcanic action, and its waste by denudation.

The first part of the theory he founded largely on generalities; the latter half, to his lasting fame, he established 90 years ago almost as clearly as it exists at the present day, though several succeeding generations of geologists failed to comprehend it.

He sums up his facts in this way:—"The Earth, like the body of an animal, is wasted at the same time that it is repaired. It has a state of growth and augmentation; it has another state, which is that of diminution and decay. This world is thus destroyed in one part, but it is renewed in another; and the operations by which this world is thus constantly renewed are as evident to the scientific eye as are those in which it is necessarily destroyed." * Intrusions of

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* 'Theory of the Earth,' p. 562. The comparison of the gradual growth of the structure of the Earth to the growth of organic beings is an analogy which has impressed many minds. Prof. Richard Owen, late of the University of Nashville, in his 'Key to the Geology of the Globe' (1857), bases his conception of the processes of Physical Geology on the analogy between the laws governing the inorganic universe with "those

melted rock and expansion by heat are given as part of the renewing activities, but necessarily only in a very general way. Since the tremendous folds of the Alpine system have been measured and drawn, it has been more usual to look upon the uplift of mountain-ranges as caused by lateral pressure, due to the shrinking of the Earth's nucleus, as already explained. Volcanic forces have therefore been relegated to the position of secondary phenomena in connection with the elevation of mountain-chains, and even according to Mallet's theory they are of secondary origin everywhere.

I trust I may be able to show that, however crude and obscure the earlier ideas may have been, there is a strong basis of truth, in the relation between volcanicity and mountain-building as cause and effect, in the way imagined, though very imperfectly explained, by Hutton.

There are no known mountain-ranges in which volcanic phenomena have not played an important part. There have also been at various geologic ages, and in different parts of the Earth, great displays of volcanic activity accompanied by the pouring out of immense floods of lava without the uprising of anything that could be properly called a mountain-range.

It would appear that when the lava has found vent at the surface, and spread itself over immense areas in massive beds, as in the Deccan in India, mountain-ranges have not been formed.

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governing the development of organic bodies." Prof. J. D. Dana appears also much impressed with the similarity between the growth of a continent and that of an organism. So long as these analogies are not pushed too far, they may be considered an aid to the understanding of the phenomena of the Universe. Sir William Dawson, in his late interesting Presidential Address to the British Association, says:—" We cannnot, I think, consider the topics to which I have referred without perceiving that the history of ocean and continent is an example of progressive design, quite as much as that of living beings."

In true mountain-chains interbedded volcanic rocks are common enough, and have formed part of the material the folding and elevation of which has formed the chains.

Volcanic orifices have been broken through old denuded rocks, and lava has been poured out over them both on the sea-bottom and on the land. The former, according to Darwin, was the beginning of the Andes, and the latter happened in the Deccan.

Are these great facts accidents, or are they susceptible of an explanation? It seems to me that they are explicable, and that they help us considerably.

Let us go back and reconsider the proposition that we started with, viz., that at or about 30 miles from the surface the rocks have such a temperature that if transferred to the surface they would assume a molten condition.

What the precise behaviour of rocks at that temperature and under these conditions of pressure would be we can only surmise; probably they would act as plastic solids.

Let us now assume that 5 or 6 miles of new rocks have been laid down upon the old, and that the isogeotherm of fusion has kept gradually rising. In the course of time the rocks, both new and old, would attain a temperature sufficient to produce movement by expansion; the strain would keep increasing in intensity until this took place. Whatever movement took place in the upper rocks would be followed by that of the mass underneath. Not only would the rigid rocks cubically expand as already explained, but the plastic mass below, kept solid only by pressure, would be exerting itself against its boundaries in all directions, so that when relief came by uplift it would insinuate itself among the newer strata in a semi-fluid state and eventually find its way to the surface, and assume a molten form.

It seems to me that unless the matter which is molten at the surface is solid at its origin, it is impossible to formulate a satisfactory explanation of volcanic phenomena. For example, many excellent geologists of the present day, feeling the difficulties besetting the secular contraction hypothesis, have suggested the existence of a fluid zone between an upper rigid crust and a solid nucleus, to aid them in accounting for the elevations and subsidences that have taken place *.

I am quite aware that this is a very imperfect account of their views; and I only mention them here to illustrate the difficulties such a fluid zone presents to my mind in explaining volcanic phenomena.

It seems to me as certain as anything in Hydrostatics that if such a zone of melted fluid rock existed, it could only be forced up to the surface from its specific gravity being inferior to that of the solid crust above.

There also seem no obvious reasons why it should rise in one place on the Earth's surface rather than another, *and least of all through the thickest strata to the highest points.*

If, however, we look upon the heated rocks as practically solid, acting under expansive strains caused by the rise of temperature, we at once see why volcanic phenomena always accompany mountain-building. The greater the weight to be overcome, the more the expansive strains will accumulate until relieved by the movement of the rocks above.

It is then that the compressed matter insinuates itself into the rocks above, and, rising to the surface in dykes and fissures, establishes itself in volcanic cones. The two phenomena are co-related, being manifestations of one and the same cause.

As the exuding rock nears the surface, it becomes molten, and acts as an imperfect fluid. It is in this way that sheets of igneous rocks are forced in along the bedding planes of the newer formations.

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* Sir William Dawson, adopting this hypothesis, considers that there are in this fluid zone (likened by him to a "thin pulp") "two layers, an inner, more dense and dark coloured, and an outer, less dense and lighter coloured" (Presidential Address, British Association, 1886).

As the cones are built up on the rising range, the lava has to ascend higher and higher before it can find vent. The weight of the column of molten rock eventually exceeds the weight of another column of the sedimentary mass. There will be a particular zone, where the two will balance each other.

Below that zone the column of solid rock will exceed in weight the column of lava in the pipe of the volcano, and therefore the rocks at a certain depth remain unaffected by intrusion in this form. Above that zone the lava-column will outweigh the solid column of the surrounding rock; consequently it will be seeking weak places, which, when found, intrusion will follow. When once intrusion begins, the superincumbent rocks will be lifted; and in this way the curious transferences of the intrusive sheet to other bedding-planes, which we know has often happened, may take place*.

Deeper down in the earth the expanding semi-fluid rock may intrude itself, and cut into surrounding strata by expansive force. In cases where the lava does not reach the surface, the same may happen.

It is thus seen how volcanic effects may be confined to a particular and well-marked region. If there were a fluid cushion on which the Earth's solid crust reposed, the crust would be in a constant state of unstable equilibrium, an improbable condition when we think of the undoubted æons during which portions of the Earth's surface have remained stable. Such, for instance, as was the case in the Peninsular area of India.

The existence of volcanoes in proximity to each other, such as Mauna Loa and Kilauea, with lava-columns of unequal height, can be readily explained if, as I have suggested, the columns of lava as they descend become less and less fluid, until approximate solidity is reached.

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* This is the case with the Great Whin Sill.

The far-famed Kilauea is an elliptical pit three and a half miles by two and a half miles, surrounded by cliffs varying in altitude from about 300 feet to 700 feet.[*] The level of the lava in this cauldron is about 3500 feet above the sea.

The summit of Mauna Loa is a broad platform about five miles by four, within which is sunk some 600 to 900 feet the great Caldera called Mokuaweoweo.

The surface of the platform is riven with small faults and cracks, and piles of shattered rock are seen on every hand. Nowhere is to be seen the semblance of a cinder cone. Many eruptions must have broken forth from the various fissures in this summit, but only here and there can insignificant traces of such catastrophes be distinguished. The absence of fragmental ejecta is extraordinary. The scattered blocks which everywhere cumber the surface appear to have resulted from spontaneous shivering of the lava-sheets by internal tension as they cooled[†]. The lava-beds in the immediate vicinity of the brink upon the summit platform wear the aspect of some antiquity. They have become brown and carious by weathering, and although no soil is generated, little drifts of gravel are seen here and there mixed with pumice. Since the Caldera was formed, there is no indication that the lavas have anywhere overflowed its rim. Yet it is a strange fact that within half a mile, and again within a mile and a half, lavas have been repeatedly erupted within the last forty years from the summit platform *from* 700 *to* 900 *feet above the level of the lake within.* The level of the summit-platform is 13,760 feet above the sea. The habit of Kilauea as well as that of Mauna Loa, and many other volcanoes, is to discharge its lavas at levels much below the summit of the main hydrostatic column in the central orifice. Capt. Dutton does not consider the Calderas have been formed by explosion, as is the usual explanation.

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[*] "Hawaiian Volcanoes," Capt. C. E. Dutton: Fourth Report, Geol. Survey of U.S., p. 104.

[†] Ibid. p. 139.

In a line extending nearly eastward from the Caldera of Kilauea is a continuous chain of pits and craters reaching quite to the sea-coast near the eastern extremity of the island. Along this line it is apparent that from time to time through the past centuries fissures have opened, disgorging lavas and building cinder-cones. The last eruption occurred in the year 1840, and was of great magnitude. It first manifested itself in an open crack about 7 miles to the eastward of Kilauea, when a small quantity of lava overflowed. At further points eastward small quantities of lava burst forth. The main eruption broke out about 12 miles from the sea-coast, and about 25 miles east of Kilauea, and an enormous mass of lava was outpoured. It spread in a stream nearly 3 miles wide, and reached the ocean at Nanawale[*].

It seems evident from the preceding facts, so well stated by Capt. Dutton, that there can be little or no hydrostatic connection between the lavas in these various orifices. If a fluid connection existed, the lava of the higher columns would presumably be emptied by the outbursts at lower levels, whereas while the level of the molten lake in Mauna Loa alters but little, that of Kilauea apparently varies more.

That these outbursts are not entirely due to steam seems clear, as so little accompanies the eruptions. The probabilities are that, after the communication has been opened between the heated matter below the zone of melting and the surface, the lava insinuates itself into the crust above in the form of reservoirs of molten rock, which continually enlarge their dimensions by melting the surrounding rock, by intrusion of further molten matter, and by lifting.

But while this heated lava is being subterraneously injected, the surrounding rocks are being heated, not only directly from the reservoir-walls, but generally from below by the transference of the heated mass to a higher level. In fact changes of temperature are ever taking place in the crust of the earth surrounding a volcano. We have seen that with *solid* strata, the ultimate result of a rise of temperature is usually folding, but where liquid rock is enclosed the compressive action of the expanding rocks about it will cause an actual ejection of part of the molten matter contained in a reservoir in the crust. That such reservoirs have existed is well known, by the immense masses of granite which denudation discloses on most areas of ancient volcanoes.

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[*] 'Hawaiian Volcanoes,' p. 125.

Such compressive action may manifest itself gradually as well as catastrophically. The outbreak of the great eruption of Mauna Loa of 1855 flowed unceasingly for thirteen months, and the lava covered an area of nearly two hundred square miles, "yet at the fountain-head the earth shows but a few insignificant wounds"*.

It is thus seen that a liquid stream may exude through rupture caused by gradual pressure, in a way quite different from the paroxysmal energy characteristic of most volcanoes. Is it not when water comes into contact with the heated rock that such tremendous explosions as that of Krakatoa in 1883 take place? And though these violent ebullitions are the most frequent in occurrence, are they not of secondary origin?

If it be admitted that molten lava in the Earth's crust may be subject to compression by the expansion of the containing rock, we at once get a clue to the intermittent nature of volcanic action. It may be explained in this way. Through the injection from below of molten matter into the Earth's crust in the form of gradually enlarging reservoirs, the surrounding rocks gets heated, and compressive strains accumulate, acting upon the lava until they end in rupture of the rocks above. The lava is then forced out, and exudes at the surface until the pressure is relieved.

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* Ibid. p. 135.

A period of quiescence then reigns until sufficient energy is again accumulated, when the action is repeated. With ramifying pipes, fissures, and veins in every direction, such as is seen in the plexus of dykes which frequently intersect strata, and often do not rise to the surface, it is easy to understand how the locus of eruption may change, though the main volcanic pipes remain constant. We know from the laccolites of the Henry Mountains that lava does accumulate in the Earth's crust in cistern-like reservoirs.

But we must not assume, because we see no folding of rocks in volcanic centres such as Hawaii, that such is not taking place deep down beyond our ken. Capt. Dutton observes with great force of Mauna Loa:—"The sea-level is an arbitrary plane, and the true dimensions of the pile are only appreciated when referred to the sea-bottom. Thus viewed, it has a base over 160 miles in length and about 130 in width, and an altitude not far from 30,000 feet, or nearly 6 miles. We may be confident that this mass has not been built up entirely by the accumulation of lavas. We have good evidence that while the lavas have been piling up, the whole mass has been bodily rising. This is in accordance with what has been observed in other volcanic regions. It was long ago pointed out by Darwin that volcanoes are situated upon rising areas, and to whatsoever extent observation has gone, this generalization is sustained by it all over the world."*

It is, however, a noticeable fact that there have been tremendous displays of volcanic energy shown by enormous exudations like those of the Deccan without the evolution of mountain-ranges properly so-called.

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* 'Hawaiian Volcanoes,' p. 195.

This is a truth to ponder over. It would seem that for the production of mountain-ranges the volcanic forces must be long sealed up, so that the heat, instead of being dissipated at the surface, may be distributed through the overlying rocks. To effectual sealing for long periods, it appears to be essential that there should be enormous thicknesses of overlying new sediments or of sedimentary and volcanic rocks in association. Such masses of new rock strengthen the crust at that part, and the energy accumulates in proportion to the resistance to be overcome; hence the enormous displays of subterranean force only seen in such connection.

According to the secular-contraction theory these points of the Earth's surface are considered the weakest. I contend, on the contrary, that they are the strongest, and that the energy of the underlying forces, so to say, is excited and increased by the accumulated mass of material.

The heating and expansion consequent upon the rising of the isogeotherms is the cause of lateral pressure, horizontal movement, and vertical uplift. It is, therefore, only when these conditions of sedimentation obtain that mountain-ranges are originated.

It seems almost a self-evident truth that if, instead of being sealed up in the Earth's crust for millions of years, the molten rock finds its way readily to the surface, there will be a loss of potential energy which would otherwise be expended in mountain-building.

Thus, where we find great surface floods of lava, the lateral movement of the rigid rocks below has been less in amount. As stated at the outset, we never find mountain-ranges originating on the sites of old denuded rocks. Sedimentation is a necessary link in the chain of cause and effect, ending in the ridging up of the Earth's crust into mountain-ranges.

It has for a long time appeared to me a weak point in most theories of volcanic action that the machinery invoked is insufficient to bring up molten matter from a great depth. Now from the universality of volcanic action at the present time and in previous geological ages, mere reservoirs in the crust unconnected with a central supply of heat are, I infer, incapable of accounting for these widely distributed manifestations[*].

Once bring the heated matter of the globe within the influences of surface action, then all the phenomena of absorption and occlusion of gases by the molten rock may take place. If, in the way I have pointed out, reservoirs of molten matter may, so to speak, be slowly pumped up from below the isogeotherm of incandescence, then the mechanical absorption of water may begin to take place, and end either in quiet ebullition or explosions of superheated steam.

Gases also may be, and most probably are, mechanically held in the original magma. If portions of the sedimentary crust become melted, gases from the distillation and destruction of organic and other matter will be set free to enter into mechanical and chemical combination with the molten rock. Prof. Judd says, "It must be admitted that we do not at present appear to have the means of framing a complete and consistent theory of volcanic action."*

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[*] Sir William Dawson, in his able address to the British Association, already referred to, has stated in an easy and clear manner the theory of the origin of mountains by the tangential pressure of a collapsing crust and the concomitant production of volcanic action. The theory evidently possesses great vitality, having withstood the assaults of Sir Charles Lyell and other authorities, doubtless from its capability, in the terms usually stated, to account for lateral pressure. The arguments urged against it in Chapter XI. remain, however, untouched, the circumferential shrinking of the underlayers of the crust, as secular refrigeration progresses, being unconsidered. If secular refrigeration fails to explain mountain-building, it necessarily fails to explain volcanic action also, as the subsidence of portions of the crust into the fluid or semi-fluid magma beneath would be insufficient to raise lava, as in Mauna Loa, 13,000 feet above the sea-level. Prof. Prestwich, in his elaborate and valuable paper "On the Agency of Water in Volcanic Eruptions" (Proc. of Royal Soc., No. 246, 1886), reasoning upon the effects of secular refrigeration, also fails to take into account the circumferential shrinking of the underlayers of the crust.

By local variations in the temperature of the Earth's crust —variations I hope I have by this time established as one of the most potent, though slow, causes of geological change— matter from below what we call the crust of the Earth may be (in fact must be) forced up in stages until it comes under the influences of surface-action. When this happens, all the recognized causes of volcanic action are brought into play. It is unnecessary for me here to dwell upon these, as the works of many geologists much more qualified to speak on the subject than I am can be consulted.

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* 'Volcanoes,' p. 360.

CHAPTER XXII.

THE LARGER BENDINGS OF THE EARTH'S CRUST.—REGIONAL SUBSIDENCE AND ELEVATION.

THE accumulation of a great thickness and extent of sedimentary deposits presupposes subsidence of large areas,—*regional subsidence* as it may be called. These movements of the crust we have good reasons to infer are not permanent bendings which have gone on increasing from the dawn of geological time.

Probably no locality could be pointed out which has not been subject to fluctuations of level on a great scale, and subsidence is but *one* phase of these changes, and may usher in a geological period. It is improbable that we shall ever succeed in tracing these movements back in geological history to the first flexure of the Earth's crust.

What are the causes of these great bendings and slow palpitations of the Earth's crust?

Some attribute sinking of the Earth when sedimentation is taking place to the gradually increasing weight of the load, the subsidence taking place *pari passu* with the loading. This might account for some of the subsidences if there were a fluid zone beneath the crust. But it is known that subsidences often take place without loading, as in some of the deep depressions in the sea-bottom.

The Mediterranean sea and the Gulf of Mexico are depressions that cannot be the result of loading. There are also immense areas fringing continents, that have been subject to fluctuating movements of elevation and depression.

The great ocean-beds themselves are not free from regional fluctuations of level, as can be well proved, and is even admitted to a limited extent, by the stoutest upholders of the theory of the permanence of oceans and continents.

To what can we attribute these extensive vertical alternations of level. Secular contraction will hardly help us here, for this would act upon the crust—even if it were an efficient cause, which I contend it is not—continuously in one direction. An earth-flexure once established in this way would go on increasing by secular shrinkage.

In reasoning upon such phenomena of our globe we are very apt to lose sight of the extreme thinness of the outer envelope as compared with the Earth's bulk. A crust thirty miles thick is proportionately a mere film, as represented by the diagram fig. 1, Plate XVIII. p. 123. Are we justified in assuming, as we usually do by mere habit of thought, that the heated interior of the globe is not subject to change? Considering the varying materials of which it is composed, as shown in the diverse composition of erupted lavas, it appears to me that an equilibrium of its constituent components has not yet been attained.

It is not improbable that large masses of the heated globe far below our thirty-mile zone undergo slow changes which produce fluctuations of temperature even in this superheated mass*. If they do, the masses so affected will fluctuate in bulk, even as the solid crust itself does, by change of temperature. Nor is this the only way in which change of bulk could take place. Chemical reaction can hardly yet have ceased, considering the multifarious materials of which the globe is composed; and chemical reaction may mean increase or diminution of bulk. All that we see of volcanic action on the surface indicates that a state of quiescent stability of the constituent matter of the Earth's interior has not yet been attained. If there be any truth in the theory of volcanic emission briefly sketched out in the previous chapter, with each lava-discharge an actual movement will take place of matter in the heated magma below the crust. The expanding plastic mass will replace the discharged lava, forcing itself upwards until it attains a fluid state by reduction of pressure. When finally the volcanic energy expends itself, as in time it will, contraction will set in and the emissions cease.

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* Mr. George F. Becker, in a paper in the American Journal of Science, February 1886, pp. 120–125, entitled, 'A new law of Thermo-Chemistry,' says:—"There is every theoretical and experimental reason to suppose that the fluid eruptive magma consists of one or more compounds differing essentially from the minerals eventually formed from it. In cooling it must therefore undergo a series of chemical and physical changes. The formation of any new stable chemical compound, whether fluid or solid, in the mass converts other forms of energy into heat; but at the same time the subtraction of any such group of molecules from the previously existing combination alters the chemical constitution of the residue."

It will thus be seen that the extravasation of lava at the surface must of necessity create an internal movement or flow of the heated magma below the crust. Such differential streams cannot but bring various components of the internal magma, previously separated, into juxtaposition, resulting in new combinations from which further chemical action may locally follow.

In this way the ejection of heated matter from the Earth's interior may be the exciting cause of further changes tending to a continuance of volcanic action.

In a globe measuring 7912 miles in diameter, with the bulk of its materials at a white heat, it would be more strange if all interaction should have ceased and the mass have become inert, than that changes and reactions should still be taking place.

Independently of the horizontal and vertical movements of the Earth's crust, ending in the ridging up of mountain-chains, there are other orographic changes constantly but slowly taking place, involving, if not such tremendous local displays of force, yet movements of matter in mass on a still more stupendous scale. There is no continent, and perhaps few islands, that do not show marks of upheaval and depression, the one by raised beaches, the other by submerged vegetation or buried river-channels of comparatively recent date. Even the stable Peninsula of India, which has been land since at least the beginning of the Cretaceous period, exhibits fluctuation of level with respect to the sea*.

In our own islands the "great submersion" occurred during the Glacial Period, reaching from 1200 to perhaps 2000 feet. Since then Postglacial movements have taken place, as shown by the submerged forests round our coasts, which are to be found in almost every estuary, and also by the existence in various localities of numerous raised beaches. Not only these phenomena, but the actual configuration of the land and the continuation of eroded river-channels far below the level of low water, complete the evidence of these areal land movements.

It is, I know, urged by some that the level of the sea has changed and not the land, but having devoted many years to the special study of these evidences of submersion, I consider that the proofs of land movement are conclusive.

Differences in radial contraction of the Earth will not account for these movements, for such a cause could work only in one direction, that is, it would constantly keep increasing the differences of elevation, whereas vertical changes recur again and again, upwards as well as downwards.

It appears to me that no explanation can satisfy the conditions of the problem as we find them in nature but that of the actual mobility of the Earth.

This was assumed by Lyell and the older geologists, but of late there has been shown a tendency to revert to the older immobile ideas of the external features of our globe.

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* 'Manual of the Geology of India,' pp. 376–377.

Some of the current views as to the distribution of land and water throughout geologic time seem to me too inelastic to explain many facts of geology, but it is not my object to discuss them here.

I can conceive no explanation of these slow pulsations of the Earth's crust—for such they are in reality—so probable as that of a change of bulk in large masses of the Earth's heated interior.

That such a mass of potentially molten matter should remain constant without the slightest change of form except that due to a rigid mathematically disposed contraction would indeed be surprising.

Changes of form by which portions of continents are submerged, others elevated, and whole areas of the sea-bottom, as proved by Darwin and Dana*, fluctuate in level, have constantly taken place. These movements may or may not be connected with volcanic action.

If we assume, as we have reason to do, that the heated interior of the Earth below the crust, solid only by pressure, is subject in large masses to change of volume by change of temperature, caused by recombination of matter taking place from time to time, many of the difficulties can be explained. An almost infinitesimal change of bulk, if the mass be large enough, would explain what to our eyes seem stupendous movements.

That these changes in the interior are to some extent influenced by changes on the surface we have seen is the case where volcanoes drain matter from below the crust, and thereby cause a redistribution of the internal magma. No doubt there is also a limit to the distortion of the Earth's form. When we consider that continents are in mean height but little raised above the surface of the sea—Europe 1342 feet, North America 1496 feet, South America 2302 feet*—it would appear that some relation must exist between their height and the stability of their foundations so to speak.

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* See Dana, "Origin of Coral Reefs and Islands," Amer. Journ. of Science, 1885; also Le Conte, ibid. Sept. 1886, p. 180.

Again, in our consideration of the origin of mountain systems, the calculations have not assumed any changes brought about by sedimentary deposition as extending deeper than 30 miles. This was intentional, as it is within this limit of depth that the cause of the phenomena of folding and local uplift must be sought. Not only mountain-chains proper but the platforms on which they stand—the whole continental system in fact covered by these deposits—are uplifted. This truth is well illustrated in the eastward approaches to the Rocky Mountains, which have long and easy gradients, though the maximum elevation of the ranges is great.

It is also strikingly shown in the Great Plateau System of Asia. Great mountain systems and continental plateaus as a whole are extremely permanent features of the Earth's surface, and there must be some cause for this stability.

The explanation that most commends itself to my mind is that there has been below the crust, out of which the mountain structure has been built, a lateral transference of material to the *loci* of the mountains and plateaus which has effected a permanent relative alteration of levels. This may result, as we have seen, from the expansion of a mass of great area thickening out by compression, under the sites of what become the highest parts of the continents.

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* Humboldt, quoted by Herschel, 'Outlines of Astronomy,' 9th edit. p. 189. There appears to be some obscurity in Humboldt's figures, most writers give half these heights as Humboldt's results. Sir John Herschel, however, distinctly states that Humboldt's figures represent the heights of the centres of gravity of the continents, and must be doubled to arrive at their mean heights. Mr. F. W. Rudler kindly informs me that Dr. Gustav Leipoldt (Petermann's 'Mittheilungen' for 1875, Bd. xxi. pp. 130–132), in 1874 recalculated the mean height of Europe with more scientific exactness of method, and arrived at the conclusion that its mean height is 296·838 metres.

Partly then, but not wholly, the internal movements are relative to those on the surface, and to the transference of material by sedimentation.

The actual weight of sedimentary accumulations such as go to form mountain systems, must doubtless to some extent affect the foundations of the Earth on which they rest.

They may cause material below the crust to be squeezed out laterally. This would seem to be the case sometimes, from the fact that occasionally the thickness of deposits ascertained by measurements in mountain-ranges exceeds the depth of the deepest part of the ocean. Indeed, if the figures are reliable, the deposits are sometimes double the thickness of the deepest soundings. The natural inference is that they have pressed down the crust by their own weight. I do not, however, attach the same importance to *loading* as a geological agent as some good geologists appear to do *. That sedimentation has not raised mountains and continents by mere weight, is shown by the fact of the highest land being composed, as we have seen, of the thickest sediments.

Bending of the Earth's crust initiated in other ways may be increased by loading, but that the crust responds in a perceptible way to every additional foot of strata laid down upon it, is too great a refinement to be probable.

The piling up of 10 miles in thickness of rock upon a pre-existent series, would doubtless compress the latter beyond its limit of elasticity. As I have shown (p. 91), solid rock subjected to such a pressure would flow in any direction on relief of the strain. It is therefore possible that such a pile of strata might assist to produce a geosynclinal by a lateral displacement of the underlying matter. But at what depth this readjustment would take place we have no means of knowing. The deeper the zone of displacement the more widely would the surrounding areas be affected, but the less would be their consequent elevation.

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* There are some excellent observations on this question, in which I concur, by Le Conte in the paper already referred to (Amer. Journ. of Science, Sept. 1886, p. 180).

The greater flexures of the Earth being partly independent of sedimentation, we can readily understand how changes favourable to a redistribution of land and sea slowly take place.

Roughly speaking, the proportion of land to sea is as 1 to 3 *. Land and Water are also so interlocked in their distribution that it would be difficult for a large flexure to take place without affecting both. The mountain and plateau systems are among the most permanent features of the Earth's surface. It follows that the subsidence of part of a continent would be immediately followed by a deposit of sediment upon it derived from these higher lands. Sea-bottoms raised into land would be denuded, and so the cycle of change would go on, subject to the controlling forces of the surface, somewhat in the way just pictured. By these various processes the extremely diversified features of the Earth's surface may have been created; and it is easy to see that, given time enough, the changes, in whatever order they happen as to *place*, would eventually affect the whole surface of the globe. If we fix our continents and fix our seas, it appears to me that, in addition to such an hypothesis being discordant with a full consideration of known facts, we limit the possibility of geological change, and render the features of the Earth's surface difficult, if not impossible, of explanation. It may not be out of place here, in connection with regional subsidence, to allude to the very prevalent notion, originated I believe by Humboldt, that the great volcanoes of the globe, being mostly distributed in a linear manner, are situated upon lines of fissure connecting them together. If this were so, it would mean the existence of fissures thousands of miles long, extending in fact over half the circumference of the globe. But such fissures would hardly be confined to the present time, and we should expect

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* 27 to 72.—A. Guyot.

In a deep road-cutting at Bidston Hill, Cheshire, I observed slickensides also due east and west, but not veined with quartz. At Beeston Castle Hill in Cheshire, I observed a slickensided face, east and west in direction, and apparently horizontal. The slickenside face seems to be here largely formed of sulphate of barium. There are also two well exposed faces showing horizontal slickensides in the quarry at Poulton in Cheshire, which the Liverpool Geological Society has had photographed. Both these faults or joints are east to west in direction, but are not parallel, and would intersect if projected into the worked part of the quarry. I have noticed horizontal slickensides in a quarry at Town Green in Lancashire, but much less perfect than those before described. All these are in the Trias.

I have also observed slickensided faces in Brandreth Delph at Parbold in the Millstone Grit. One face was due north and south, the striæ dipping 18° south, the same way as the beds. The face of the fault is not a clean cut, but has prominences, and it is these that have been rubbed or ground together.

In a quarry at the top of Harrock Hill, at Parbold, I noticed a slickensided face with a direction east 20° south, the dip of the striæ being 10° easterly, about the same as the bedding.

The Carboniferous system, to which these last mentioned rocks belong, is much more disturbed than the Triassic sandstone.

In the Wenlock Limestone (Silurian) I noticed in a quarry at Much Wenlock a slickenside having a direction north-east to south-west, dipping only 7°.

Very little attention seems to have been hitherto given by geologists to these indications. Indeed they are such as to escape notice if not particularly looked for. I feel quite sure that these records of rock-movements would be found, if sought for, to be very general, and would help us considerably in interpreting the dislocations to which the rocks have been subjected *.

The wonderful porcellaneous nature of the slickensided face when on sandstone rocks—so hard, smooth, and polished—is not easy to account for; often all indications of a granular nature seem to be obliterated †.

I have been unable in any case to calculate the amount of horizontal throw that has produced the markings. It may often be small. It is easy to understand that a mass of sandstone, subject to lateral pressure, unless of a very homogeneous nature, will undergo a differential movement of the blocks into which it is naturally divided. Being individually rigid, they will be ground together. Most of the slickensides noticed are in Keuper sandstones. I have observed none on the pebble-beds of the Bunter, which are much more massive; but I do not happen to have had much opportunity of looking for them in this division of the Trias since my attention was drawn to the phenomenon ‡.

It will be noticed that the pressure has in most cases acted at right angles to the main faulting and parallel to the bedding. From this I infer that the main north and south faulting is subsequent to the transverse striæ. The main faults are all normal and contraction faults, and often show splendid vertical or inclined slickensided faces.

These striæ are vertically at considerable angles to the pressure slickensides which it has been the object of this chapter to describe.

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* In a letter to the Geol. Mag. July 1886, Mr. Skertchly states that he and Mr. French have discovered "widely spread surfaces of chalk slickensided horizontally in the neighbourhood of Sutton, Surrey."

† I have since found specimens in which, apparently by the decay of some of the constituents of the rock, the granular nature is perceptible—grains of quartz appear with polished faces—perfect planes flush with the general face, like pieces of marble in a mosaic.

‡ Sometimes the broken rock in a fault is slickensided at various angles and planes by the crushing together of the fragments.

CHAPTER XXIV.

SLATY CLEAVAGE AND FOLIATION.

It will now be necessary to briefly discuss the relation of cleavage to mountain-structure.

So many distinguished men, both geologists and physicists, have devoted attention to the phenomenon of cleavage that it will be somewhat difficult to say anything new on the subject.

Mr. A. Harker [*] has lately given us an able *résumé* of the various facts and theories relating to slaty cleavage, so that it is unnecessary for me to traverse them here.

It is, however, important to note that the concensus of opinion is in favour of slaty cleavage being a mechanically induced structure, due to lateral pressure. In proof of this it is contended that the cleavage-planes are always at right angles to the pressure, and it is pointed out that the distortion of imbedded fossils is always in the direction of the cleavage-planes. It is also maintained that the material of the slates, while being compressed at right angles to the cleavage-planes, has been extended in a direction towards the vertical, but not laterally. There has consequently been an internal movement or flow of the rock upwards, so that cleavage, according to this view, is allied to fluxion-structure.

That slaty cleavage is intimately related to lateral pressure surrounding circumstances seem to show, but that it is due to actual flow of the material of the rock cannot, I think, be so easily upheld.

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[*] "On Slaty Cleavage and allied Rock-structures," British Association Report, 1885.

If I have in any way adequately explained the movements the rocks have undergone in highly plicated regions, it will be seen that the effect of pressure is not in every case to extend the beds at right angles to the direction of pressure. In some cases it does—indeed we may go so far as to say in many. In the complicated bending, twisting, packing, and folding of beds of moderate thickness in contorted regions, the flow of the material of the beds has been diverse in direction at different times in the same bed. How could such internal movements produce parallel planes cutting through the rocks independently of their bendings, and extending over vast regions? Rather, if formed while these movements were progressing, they would lack both parallelism and straightness of direction*. The divisional platy structure would be in tortuous sinuosities very different to slaty cleavage, by which slabs almost true planes, a fractional part of an inch in thickness and many feet square, can often be split out of a block of slate-rock.

If, on the other hand, we hold that slaty cleavage has been impressed upon the rocks after the main plications have been completed, we are landed in the dilemma of having to believe that the folded region, once the folding is completed, acts as a homogeneous body, and expands upwards along the cleavage-planes without regard to the folds or to the angles at which the various beds lie †.

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* See description of Plate XLII. at the end of book.

† Mr. W. Gersholm Collingwood observes, with respect to cleavages in the Alps ('Limestone Alps of Savoy,' p. 96), the cleavages in the Oxfordian and Neocomian in the Valley of Cluses seem to dip at the same angle, notwithstanding the tilt, or even contortion, of the beds. "That is to say, that not only did the pressure which contorted the strata fail to produce this cleavage, but this cleavage seems to have been created after the contortion by causes of quite a different nature."

Doubtless the distortion along the plane of cleavage often shown by fossils, and accompanied sometimes by their separation into fragments, has been due to a flowing of the rocks in the general direction of the cleavage-planes. But may not this be in cases in which the direction of movement happens to coincide, which, no doubt, it often does, with the cleavage-planes? It does not follow that the one is identical in direction with, or the direct consequence of the other.

It appears to me that slaty cleavage is due to a molecular rearrangement in some way related to pressure, but taking place in the rocks after internal movement has ceased.

Is it not as likely to be connected with a constantly sustained pressure for long periods and an after-relief?

I find it difficult to believe that the distortion of the fossils has taken place after the plication of the beds has ceased. The distortion would be more likely to take place *pari passu* with the plications, and, if so, the phenomenon of fossil distortion and that of slaty cleavage are not so directly related as at first seems likely. It is a very remarkable fact that steel plates, bars, or angle-iron which have stood all the tests of bending, hammering, &c. satisfactorily, may sometimes, after being left for a night lying in a yard, be found in the morning rifted by internal movements. How can this curious fact be accounted for? There is no doubt we are extremely ignorant of the nature and causes of molecular change, and we may as well confess it.

In the neighbourhood of Llangollen, the cleavage which has affected the Upper Silurian rocks commences at the slate quarries of Llansaintfraid Glyn Ceriog, 2½ miles south of Llangollen, at the low angle of from 27° to 30° N.E., the direction being subject to a little variation. The bedding dips from 15° to 18° N.E. by N., being also subject to variation. The cleavage dip gradually increases (with variations) as we proceed northwards until at the slate quarries on the north flank of Moel-y-faen, near the Ruthin Road, a distance of nearly 7 miles in a direct line N. by W., it reaches 56° N. by E. In these large quarries the rock is much affected by anticlinal and synclinal folds, the cleavage nevertheless being constant in dip. About 1¼ mile south of these slate quarries is a large flagstone quarry of clay-slate. These flaggy beds dip 75° N. The flags possess an undeveloped cleavage, but separate in the bedding planes.

In the slate quarries (worked by galleries) near the summit of Moel Ferna, the dip of the cleavage is, as ascertained by me, about 18° N.E. by N., but varies a little. The beds dip from 12° to 14° N.N.E. These quarries are about 6 miles, almost directly east, from those at Glyn Ceriog.

The interest of these examples lies in the low inclination of the cleavage on the southern line between Moel Ferna and Glyn Ceriog. Sedgwick was of opinion that cleavage as originally produced was always nearly vertical. It is quite evident that in these examples it cannot have been so, for the beds are very little disturbed where the low inclination occurs. It therefore follows that if the cleavage was induced at right angles to the pressure, the pressure in this case must have acted in a direction towards the vertical. Thus the cleavage may be connected with detrusive action during the uplift of the Berwyn dome. In Glyn Ceriog quarries splendid examples of slickensided beds occur. In one case (middle quarry) the bed dipped 20° N., and the striæ 18° N. by W.

Mr. William King, in a memoir "On the Kadapah and Karnúl Formations in the Madras Presidency" *, gives examples of undulating cleavage-planes with interstitial quartz affecting the clay-slates on the eastern flanks of the Nullamullays. The cleavage also affects the limestones and, least of all, the quartzites. He observes, however, that in the

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* Memoirs of the Geological Survey of India, vol. viii. part i. p. 137.

latter the cleavage-structure is at times very distinctly superinduced, more particularly when the strata are much contorted and reduplicated. "The quartzites are very seldom strongly cleaved until they are sharply contorted or crushed up in themselves, in the same way as is often the case with the slates." These examples also tend to show that the cleavage is related to the pressure, but induced after the movement of contortion has ceased.

The late Professor King, of Galway, considered that cleavage was related to jointing *, and that cleavage-planes were compressed joint-planes. He pointed out to me some very remarkable jointed Carboniferous Limestone in a field between Galway and Oranmore † that might have been mistaken for vertical laminated bedding. He looked upon the divisional structure of the bands of rock opposite the South Stack, Holyhead (Plate XXXIV. fig. 1, p. 202) also as jointing.

Without being able to follow my revered and lamented friend to the full consequences of his reasoning, I consider that jointing and cleavage are physically related phenomena. Slaty cleavage, as already suggested, may be a molecular rearrangement brought about by pressure, while jointing is probably a sort of rude and imperfect crystallization on a large scale.

To conclude, bedding-lamination arises in the case of pure sand from the arrangement of the constituent grains in parallel planes. The application of great pressure has a tendency to reverse this arrangement of the grains to planes at right angles to the pressure. Subsequent metamorphism will tend to develop the fissile structure, because interstitial crystallization will develop a mineral arrangement in the same direction. It will thus be seen that pressure and metamorphism act in a common direction towards the production

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* "On Jointing and its Relation to Slaty Cleavage," 'Transactions of Royal Irish Academy,' vol. xxv., 1875.

† Ibid. p. 635.

of slaty cleavage. It is quite impossible to do more here than touch the skirts of the subject, either as regards slaty cleavage or jointing.*

Foliation.—The relation between foliation and cleavage has been speculated upon by many geologists. "Dr. Darwin found in South America immense tracts of intensely metamorphosed schists, the folia of which had every one of the distinguishing characters of cleavage laminæ; their strike was uniform over large areas, and parallel to the leading physical features of the country, and in all cases which he saw, where masses of cleaved and foliated rocks alternate together, the cleavage and foliation were parallel." †

The late Mr. David Forbes exposed amorphous soapstone to a moderate heat, not exceeding redness, for some months under a pressure of from 7 to 12 lb. per square inch, and obtained an aggregate of finely-developed crystalline foliæ of a brilliant white or greenish colour, identical with talc—in fact, a talcose schist; under similar circumstances clay-slates were converted into rocks possessing a beautiful parallel structure, closely resembling gneiss ‡.

It would appear from these experiments and from observations in the field that foliation may be superinduced on either cleavage or bedding. Foliation-planes have not the mathematical truth of cleavage-planes. Highly crystalline rocks are the most frequently foliated, and it is difficult not to believe that these varying mineral laminæ have followed and developed a structure which formerly existed in the rock.

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* Among many others, the following papers may be consulted with advantage:—"On the Absence of Joint Structure at Great Depths," by W. O. Crosby, Geol. Mag. Sept. 1881; "On the Classification and Origin of Joint Structures," Crosby, Proc. Boston Soc. of Nat. Hist. vol. xxii., Oct. 1882; "On the Origin of Jointed Structure," by G. K. Gilbert, Am. Journ. of Science, July 1882, p. 50; "Post-Glacial Joints," Ibid. Jan. 1882, p. 25; "Jointed Structure in Clay and Marl," by John Le Conte, ibid. 1882, p. 233; "Notes on Joint Structure," W. O. Crosby, Proc. Boston Soc. of Nat. Hist. vol. xxiii. 1885, p. 243.

† 'Physical Geology,' Green, 2nd ed. p. 422, see "Cleavage and Foliation"; 'Geological Observations,' pp. 460–469.

‡ Ibid. pp. 422, 423.

It is therefore probable that foliation may sometimes follow a fluxion-structure induced by pressure. We have seen what extraordinary changes Archæan rocks have been subjected to; how they have been compressed, twisted, and squeezed out. It is, in fact, the numberless changes which they have undergone that makes them so difficult to read.

Whether foliation represent bedding or other structure is a question to be settled in the field from each particular example. It is impossible, in our present state of imperfect knowledge, to lay down any general rule.

Daubrée unites the phenomena of foliation and cleavage under the general head of "schistosité." He appears to consider that both are produced by an internal sliding of the substance of the rock, and his experimental attempts to produce foliated structure in clay showed that the compressed mass should be endowed with a certain degree of plasticity—too dry, it breaks; too soft, the laminæ cannot separate. Experiments were made by "squirting" clay by a hydraulic press. Plastic clay and quartzose sand produced a fibrous texture, with the laminæ parallel to the pressure.

Dr. Sorby, in his Presidential Address to the Geological Society, 1880, p. 84, says that the "connecting links between slates and schists clearly show that foliation is essentially different from either stratification or cleavage;" and he is of opinion that "there is sufficiently good proof that the schists of the central Highlands of Scotland were originally slates" (p. 87). He distinguishes between "stratification-foliation" and "cleavage-foliation." In the former the large flat crystals of mica lie in the plane of the beds of different mineral nature. Some specimens obtained between Aberdeen and Stonehaven show in the same thin section both stratification-foliation and cleavage-foliation. In some cases the stratification-foliation has been bent into small contortions, and only a little mica has crystallized along the planes of discontinuity. "The differences in the character of the foliation in the different specimens now described appear to have depended on whether or not the rock became completely solid and crystalline before it was compressed, or was compressed before it became solid and crystalline" (p. 91).

CHAPTER XXV.

EARTHQUAKES AND THEIR CAUSES.

It is a very curious fact that more than one eminent geologist has spoken of Earthquakes as being the *cause* of subsidence, of elevation, or of fracture *.

This appears to me—leaving out of account minor secondary effects—to be putting the effect as the *cause*, and is, at least, a loose unscientific way of speaking.

It is not my intention to write a treatise on earthquake motion, but it seems necessary to trace the connection existing between the causes producing the elevation of mountain-chains, the phenomenon of faulting, and that of earthquake tremors.

Prof. John Milne, who has devoted great attention to Seismology, tells us that the crust of the Earth is in almost a continual state of tremor. This, in itself, shows the crust to be an elastic solid with the strains so nicely balanced that it is easily affected. If I have not entirely failed in my object, the reader must by now be convinced that, through small changes of temperature, the internal strains of the strata of the Earth's crust are continually changing. Let us imagine an expansive stress to be set up in a group of rocks possessing the rigidity of those near the surface.

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* Since this was written, Prof. John Milne's valuable work on 'Earthquakes and other Earth Movements' has been published in the International Scientific Series. Even here a list of "geological changes produced by Earthquakes" is given (p. 161), in which great subsidences and elevations of the Earth figure as the *result* of Earthquakes.

This strain will accumulate by slow degrees until it is just more than equal to moving some part of the mass. The pent-up force will then, obeying some external liberating influence, affect the rocks suddenly in its effort to regain equilibrium. A small movement, if it took place suddenly in a sufficiently large body of rock, would have a great effect in communicating a vibratory or wave-like motion to the Earth's surface. The greater the strain from which the crust is relieved, the greater will be the vibratory and elastic movement*.

It is not my object to treat of the earthquakes that usher in volcanic action. The subject has been fully discussed by Mallet, Milne, Judd, and others, and I could add little to what has been already said. But it is from the earthquakes that are unaccompanied by such outbreaks that we shall gain the most knowledge for our present purpose. Leaving the volcanic centres and casting our eye over the land areas, we shall find that the countries which are most subject to these dreadful tremors are precisely those in which there is a development of the later formations, and particularly the Tertiary†.

Peninsular India, as pointed out by Mr. Blanford‡, is comparatively little affected by earthquakes, while the whole country in and beyond the Gangetic plain is very much subject to them.

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* The external liberating influence here spoken of, the "hair trigger" so to speak, might be a change of barometric pressure, a change of external temperature, the Moon's attraction, &c. See 'Earthquakes' by Milne, already referred to, Chap. xvii.

† As if to emphasize this statement, the earthquake in Georgia and South Carolina which occurred on the night of August 31, 1886 (described as the most severe on record in the United States and affecting an area of a million square miles), originated under the Tertiary rocks of the Atlantic seaboard, being most severely felt at Augusta and Charleston.—See 'Nature,' Sept. 9, p. 460.

‡ 'Manual of the Geology of India,' vol. i. p. lvi.

This is exactly what *à priori* would be predicated according to the views already expressed. Peninsular India is very old land; Extra-Peninsular India, on the contrary, is, comparatively speaking, young. It has been subject for a lengthened period to tremendous subterranean forces which are not yet exhausted. The isogeotherms are probably sinking lower and lower. The earthquakes are most likely connected with subterranean contraction, for they seem to be accompanied more by subsidence than by elevation, like that which produced the Runn of Cutch *.

If we consult the map of Europe, Western Asia, and Northern Africa, we shall find that it is those countries in which the newest deposits are best developed that suffer most severely from earthquakes, namely, Spain, Switzerland, Algeria, and Syria.

Lisbon is built upon Tertiary rocks. To go no further than our own country: the great earthquake that affected the south-eastern counties of England in 1884 appears to have originated under the older Tertiary deposits †. The great earthquake of Lisbon was accompanied by subsidence of the ground.

The earthquake which devastated the valley of the Mississippi, so well and graphically described by Lyell, was on the site of Tertiary rocks. If we trace the earthquake regions round the world, we shall find that they are, to a large extent, conterminous with the newer rocks ‡.

Without pressing this parallelism too closely, I think we are justified in suspecting a connection between the two phenomena. The forces which have elevated these deposits into land are now subsiding. With their dying out and the gradual loss of temperature or sinking of the isogeotherms is an accompanying loss of bulk in the subterranean rocks. This loss must be compensated by the closing in of the crust by faulting or by readjustment of strains that may not go so far as perceptible faulting.

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* Lyell, 'Principles,' 10th edit., vol. ii. p. 102.

† The area of structural damage extended over some 50 to 60 square miles in north-west Essex, the geological formation being London Clay overlying the Chalk (see plate iii., Report on the East Anglian Earthquake by Meldola and White).

‡ Prof. Milne's map, showing the seismic and volcanic areas of the Earth's surface, should be consulted.

Mr. Gilbert, speaking of the connection of fault scarps with earthquakes, says:—"The fault scarps of the Sierra Nevada follow the eastern base, and it happens that one of them has been formed since the settlement of the country. It occurred in 1872, and produced one of the most notable earthquakes ever recorded in the United States. The height of the scarp varies from 5 to 20 feet, and its length is forty miles. Various tracts of land were sunk a number of feet below their previous positions, and one tract several thousand acres in extent was not only lowered, but carried bodily about 15 feet northward. The ground was cracked in various directions, and several springs permanently disappeared." There was only one violent shock, and the damage was all done in a few seconds; but for two months there were occasional tremors*.

Earthquakes, according to calculations by Mr. Mallet, originate at depths varying between eight miles and thirty miles below the Earth's surface.

Their origin is therefore mostly in the rigid crust. Horizontal expansion or contraction acting suddenly may produce earthquakes, or they may result from deeper-seated cubical contractions in which the rocks above can only adjust themselves to the altered condition of volume by subsidence.

We thus have a *vera causa* for the earthquake blow.

We have seen that a rise of temperature of 100° F. will produce an expansion of 2·75 feet per mile in average rock.

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* G. K. Gilbert, "Earthquakes of the Great Basin," Amer. Journ. of Science, Jan. 1884, pp. 51–52.

A lowering of temperature to the same extent would have to be met by an equal contraction. It is thus easy to see that very small changes of temperature may produce great effects. A loss of 10° F. would mean a contraction of 0·275 feet per mile. Extend these movements over a sufficiently large area and the effect would be tremendous. At the depth of eight miles the rock must be in absolute contact throughout by compression, so that either expansion or contraction would be continuous over immense areas. This is a very moderate depth for an earthquake origin or centrum. Nearer the surface the discontinuity of the rocks would not allow them to act as homogeneous bars or sheets. The rifts in the surface of the ground, spoken of as so often accompanying earthquakes, may arise from the greater vibration at the surface. It is well known that such rifts are commoner near cliffs and river-margins than elsewhere.

Changes of temperature in a great mass of rock, in some cases perhaps measuring thousands of cubic miles, will account for the persistence of earthquakes and earth tremors over long periods of time—for days and even months. The mass will not adjust itself by one movement; internal adjustments of portions of the mass may go on for a considerable length of time. A common illustration of this may be obtained from an ordinary grate, which in cooling often contracts with a crackling noise *.

That earthquakes result in each case from a continuous cause fluctuating in intensity is suggested by their periodicity †.

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* Mr. Horace B. Woodward, F.G.S., in the 'Transactions of the Norfolk and Norwich Naturalists' Society,' vol. iv. says:—"Probably we shall not be far wrong if we attribute the recent earthquake in Essex to one or more subterranean rents produced by shrinkage, which led to no material shifting of the rocks, and which, owing to the tenacious nature of the subsoil at Colchester, chiefly London Clay, did not manifest itself in any conspicuous manner at the surface."

† 'Earthquakes' (Milne), p. 245.

They are most frequent in those countries where changes of temperature in the crust are likely to occur the oftenest and with the greatest intensity. These changes, we have seen, produce increase or decrease of bulk in the rocks affected, and the crust, from time to time adjusting itself to the new conditions, is agitated and trembles. There appears to be no other cause so universal and constant to account for earthquakes; indeed, knowing that these forces are in existence, may we not rather wonder at the general stability of the surface of the earth, rather than at its occasional instability *.

Before this view impressed itself upon my mind I was quite at a loss to imagine what could produce the "sudden blow" seismologists speak of: we have been too prone to associate these phenomena with explosions of superheated steam, which, of course, cannot account for earthquakes away from volcanic centres. We now find that earth-tremors and earthquakes are a necessary consequence of the readjustment of portions of the Earth's crust to altered conditions of bulk produced by local expansions and contractions †.

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* Prof. Milne suggests "slow elevations" as a cause of earthquakes. "By various causes the rocky crust is bent until, having reached the limit of its elasticity, it snaps, and in flying back, like a broken spring, causes the jars and tremors of an earthquake" (p. 348); but this cannot be of frequent occurrence.

† Prof. Milne enumerates "expansions and contractions of the Earth's crust" (p. 277) as causes of earthquakes. It is merely a general statement, as he enters into no further details under this head.

Prof. Joseph Le Conte considers that the gravitative settlement producing Normal Faults "is by far the most probable cause of most earthquakes," Amer. Journ. of Science, Sept. 1886, p. 179; but earthquakes may occur without preceptible faulting, as I have shown.

CHAPTER XXVI.

SEDIMENTATION, UPHEAVAL, AND SUBSIDENCE.

From what has been already advanced, we see plainly that mountains are never built excepting where great and long-continued deposition has taken place. Sedimentation is therefore a necessary precedent condition to mountain-building. Not only must there have been great thicknesses of rock laid down on perhaps very old denuded land-surfaces, but the deposits must also have had great superficial extent. It is only necessary to look at the geological map of the United States to be convinced of this great truth. Between the 29th and 49th parallels of North latitude and 97th and 111th meridians there is an almost uninterrupted area of Cretaceous rocks. Underneath them in many places, as we have seen, Jurassic and Triassic formations occur reposing upon a plicated and denuded platform of Carboniferous rocks. These plications seem to have been synchronous with those of the Appalachians.

It would appear therefore that, since the denudation of a continent formed and upraised out of Carboniferous rocks, more or less continuous deposition took place over this area until the close of the Cretaceous times. This eventually led to expansion and earth-movements, giving birth to the varied mountain-systems of the Western territories. The newly-formed crust was compressed and more or less flexured from the Rocky Mountains westward, and at the same time the whole area was being elevated. The geology of the United States westward of the Great Basin has not yet been systematically surveyed, so that I do not propose to enter upon a discussion of it.

It is unnecessary for my present purpose to say more than this. These Mesozoic deposits extend northward into Canada to the 56th parallel, and southward beyond the boundaries of the United States. Indeed, the whole western coast of North and South America may be considered as one great geological province.

The main axial lines of the mountain-ranges from Tierra del Fuego to Alaska have a north-and-south direction, following in that respect the main axes of the areas of deposit.

Under the whole of these great areas, after deposition had been completed, the isogeotherms had risen sufficiently to counteract the previous tendency to subsidence, which,—perhaps to some extent assisted by the accumulated weight of the deposits,—had characterized these vast areas of the Earth's crust.

The rising of the isogeotherms would in the commencement only affect the underlying portions of the land, and would probably be confined to a zone considerably below that of the base of the new deposits. The plastic mass below the rigid crust would be the first to feel the influence of the rise of temperature.

Through the boundaries of the lenticular mass affected being confined, the vertical expansion (as explained, p. 114) would be multiplied in threefold the ratio of the linear expansion. The result would be principally upheaval, by which the submarine deposits would become elevated into dry land. As the underlying beds communicated their heat to the overlying deposits they also would begin to be affected; lateral expansions in all directions would set in to the extent of about 2·75 feet per lineal mile per 100° F. As I have clearly shown by the experiments in heating sheet-lead, the transverse force of expansion would, through acting over a greater section of rock, determine the axis of upheaval in a longitudinal direction. The total linear expansion along the greater axis would have to be compensated, first, by undulations and similar cross-ridgings, secondly by turns and twists in the direction of the ranges, and thirdly by an actual conversion of longitudinal into transverse motion. That this latter actually takes place is well shown by the forms assumed by the sheets of lead experimented upon (Plates III. to VI.); otherwise it would be impossible to account for such a perfect semilune anticlinal as is figured on Plate VI. and described on p. 15.

While these internal expansions are going on—an expansion within strictly confined boundaries is the same in effect as the application of a compressive force, excepting that it more perfectly affects every component molecule of matter—the plastic mass below the Earth's crust will be under an extreme compressive strain. It will be seeking every weak place to burst its bonds.

The Earth's crust will then be riven with fissures and dykes, and bored by volcanic pipes until, through lava overflowing at the surface, the pent-up forces temporarily exhaust themselves. The removal of a great heated mass of rock—such as happened in the great lava-flows of the plains and plateaus of Western America—from the crust to the exterior must lower for the time being the temperature of a large portion of the crust in the locality where it occurs. Local intrusions will raise the temperature at particular parts. The temperature will never be constant; it will fluctuate, and these fluctuations mean increments of expansion and contraction. Such changes, however small, will, when added together, leave their marks on the structure of the rocks and the orography of the districts.

But mountain-building is a slow process; it has been going on in one form or another in Western America from the close of the Cretaceous to the present time. Faulting as well is flexing is an integral part of mountain-building.

Although, as I have shown, normal faulting is primarily due to contraction, it may go on while the range is being built up as a whole. Part of the structure subsides while another is being built up. Reversed faulting is due to the same compressive forces that form the folds and flexures.

While these movements of elevation, expansion, and contraction are going on, the strata are being injected with dykes, sheets and cisterns of molten matter, and further consolidated to be still further affected by the rising heat from below.

Although these fluctuations of temperature occur over and over again during the erection of a mountain-range, as I have shown, the tapping, so to speak, from time to time of the molten matter of the Earth (potentially molten below a certain level), though it temporarily exhausts the heat through the cubical mass of heated rock each time abstracted, draws further supplies from below the crust. There is an indraught of heated matter towards the lower end of the volcanic pipes or fissures.

In this way we can understand how it is that volcanic districts have apparently continued active through millions of years, but perhaps not without intermission.

But while these forces of upheaval and faulting are in energetic action, the no less powerful but unobtrusive forces of denudation are at work carving and levelling as the mountains are ridged up. The upper beds of rock remain unaffected by the internal heat, the surface temperature being the mean of the temperature due to the latitude and climate, and therefore only subject to climatic changes. While therefore the rocks below suffer from powerful compressive strains, the surface rocks, having to adapt themselves to the flexures that originate from below, are subjected to tensile strains. Possessing but little elasticity they fracture, and the fractures necessarily occur near the apex of the anticlinals or monoclinals.

The agents of denudation therefore have free play. The fissures are soon widened and deepened, so that in strata subjected to long continued denudation what originally were hills often become valleys. Scarped faces are in this way formed, and the strata are worn back laterally.

A reference to any geological map in which the strata are domed up, as in the Woolhope dome, the Weald of Kent and Sussex, and other examples already given, will enforce this great truth.

Indeed, unless a scarped face originates in a fault (and of these the only example I know of in this country is the Craven and its continuation, the Pennine fault), it is the only way in which a true escarpment can arise. The remarkable Oolitic escarpment, which stretches in a more or less perfect form from the extreme south-west of England northward into Yorkshire *, I attribute to a similar cause. There is no doubt that the Oolites originally stretched out far over the western, and perhaps north-western, counties of England and have been denuded therefrom. When we come to consider the geological history of the British Isles this will be further dwelt upon.

While the whole Western Territories of the United States were being upheaved and flexed, the atmosphere, rain, and rivers, acting both chemically and mechanically, were at work carving the roughly modelled blocks into new forms: so varied are these forms that to enumerate them would demand a treatise. Those who wish to know more about the scenery of America in relation to its Geology, have only to consult the splendid volumes published by the United States Government.

During the upraising of the mountain sierras and plateaus, immense denudations took place and redeposit of sediment in great Eocene lakes. Then occurred volcanic overflows burying large areas of country under floods of lava, repeated

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* Ramsay, 'Phys. Geog. and Geol. of G. Britain,' 5th edition, p. 316.

at intervals sufficiently far apart to allow of the previous overflows being largely swept away by denudation.

Finally subsidence took place, giving birth to great Quaternary Lakes—Bonneville, Lahontan, and a host of others.

That subsidence from time to time and on a great scale has been an integral part of the geological history of these mountain-districts is undoubtedly true. The subsidences have arisen from local contractions and gravitative settlement in turn influenced by the differential strength of the foundations on which the upper strata rest. With a continually increasing compression, such as is invoked in a secular shrinkage of the earth, or by a change in its form, subsidences of this nature, and on such a vast scale, could not occur; hence to the other defects of such explanations this fatal one must be added.

Supposed Effects of Removal of Weight by Denudation.

We have seen that while denudation progresses, weight is being removed from an uprising district. Is there here any relation of cause and effect? Possibly there may be some at a particular period of its geological history. Still I do not attribute great geological importance to the removal of weight during elevation.

We know that the whole of an elevated region eventually gets levelled down, approximately, to a plane, and that it does not, after a certain period, continue to rise higher and higher above the sea-level, as the theory of elevation and subsidence by loading and lightening would seem to demand. Some of the oldest countries are nearest to the sea-level. The bed of the Mississippi is at an exceedingly low gradient, so is that of the Ganges, and both are at their embouchures far below the sea-level. If the deltaic deposits and the great submarine deposits that take place at their mouths * have the effect some geologists imagine they have, we should expect their outlets to become depressed as we find they are, but should also expect their upper tributaries to be at the same time elevated and the grade of the main river-bed increased. As a matter of fact the grade of the old bed of the Mississippi is less even than the very low grade of the present river [*].

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* See "The North Atlantic as a Geological Basin." Proc. of Liverpool Geol. Soc., Session 1885–6.

Again, if there be no accession of heat from below, as denudation takes place the isogeotherms must sink and contraction set in; this seems to be what really happens after the internal fires have spent themselves.

Supposing that every other condition remained the same, the removal of a very large bulk of matter from one portion of the Earth's crust to another would no doubt, as pointed out by Sir John Herschel, have an influence upon the Earth's crust [†].

The effect being complicated with other forces, it is difficult to separate the one from the other. I am satisfied that this cause can only at the best give a very partial explanation of the complicated phenomena it has been the object of this work to investigate [‡].

It may be pointed out that the removal of 30,000 feet of rock from the Uinta Mountains has not been followed by an equivalent uplift, if referred to the sea-level.

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[*] 'The Mississippi River during the Great River Age:' Prof. J. W. Spencer.

[†] 'Physical Geography,' 5th edition, p. 116. See also the following papers:—"Accumulation and Denudation," Dr. C. Ricketts, Geol. Mag. 1883. 'Palæontology of New York,' vol. iii., Introduction, Prof. James Hall. Also various articles on this subject in 'Nature' by Mr. Starkie Gardner. "Cause of the Depression and Re-elevation of the Land during the Glacial Period," T. Jamieson, Geol. Mag. 1882.

[‡] Since this was in type, Prof. Joseph Le Conte has expressed similar views. He says (Amer. Journ. of Science, Sept. 1886, p. 181):—"The fundamental cause of subsidence and elevation over great areas must therefore be sought elsewhere, although doubtless weighting and lightening, by adding to the force or lessening resistance, will cause these movements to go further than they otherwise would."

Sir John Herschel considered that the force which sustains continents is one of tumefaction *, and this view is consistent with that held in this work; for if these large irregularities of the Earth's surface result from the cubical expansion of deep-seated matter, the total weight of the area would remain the same, its specific gravity being reduced. This theory, as already pointed out, does not apply to mountain-ranges, which largely result from an actual accumulation of material by lateral transference.

* 'Physical Geography,' 5th ed. p. 15.

CHAPTER XXVII.

WHENCE THE MATERIALS FOR MOUNTAIN-BUILDING COME.

Leaving out of account the igneous rocks, the whole of the materials of which a mountain-district or part of a continent is built have been transferred either from contemporary land-areas or from coast-lines. It is now an acknowledged axiom in Geology that the land, through the atmosphere, rain, and rivers, rather than by sea-coast abrasion, supplies by far the greater part of the materials for the formation of new deposits. If, therefore, we find a land-area composed of immense tracts of new deposits elevated from the sea-bed, we may reasonably look for the continental area that has supplied the materials out of which the new lands have been built. There appears to be little doubt that the north-eastern part of North America formed part of the land-area or areas which contributed the materials for the formation of the rocks overlying the Carboniferous of the western half of that continent. It is now a much denuded land-surface, worn down over vast tracts to the oldest known sedimentary rocks. Immense areas of Laurentian rocks have consequently been exposed. Undoubtedly, as we have seen by all available evidences, these rocks could not have attained their present highly crystalline and contorted condition except at a very great depth below the surface. Probably they have been again and again buried and as often denuded.

It would appear that while the Carboniferous rocks of Western America sank beneath the waves to be buried under new deposits, the same formation in the eastern and north-eastern parts of America remained land.

If this view be correct, the drainage must then have been principally from the east westwards, and the eastern land have been much more elevated than now. The Appalachians may have formed part of the great divide of those early days. The attempt to construct geographical maps of geological periods is not often attended with success. At a future time, when geological knowledge is much extended, it may be possible to sketch out rough outlines with some approximation to certainty, but a great deal remains to be done before this can be attempted.

In the meantime, I can only express my view that the greater river-systems, like the mountain-systems, will prove to have their origin in the Tertiary period. If this be so, the Mississippi, the Amazons, and La Plata were not in existence when the great deposits parallel to the western coasts of the two Americas were being laid down *.

That the land from which the western deposits were obtained was of much greater area than the portions of the two Americas at present uncovered by deposits later than the Carboniferous, we may justly assume. There are two elements in the problem in which our knowledge is more than defective—it is *nil*—namely, the extent to which the deposits later than the Carboniferous extend westward under the Pacific, and the distance to which the land-area to the eastward which supplied them extended where the Atlantic now rolls. That it did extend further eastward is reasonably probable. The indentations of the eastern coast in North America, the existence of the island of Newfoundland, composed of the older gneisses and Palæozoic rocks, the Falkland Isles in South America, of Palæozoic age, and, still further, the island of South Georgia, 1200 miles to the eastwards of Cape Horn, and composed of clay-slate, afford indications which the geologically constructive mind will not fail to utilize *.

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* Ramsay was the first to scientifically investigate the history of great river-valleys.

It seems highly probable that North and South America formed in Cretaceous and Tertiary times two distinct continents, stretching eastward into the Atlantic. In the sea which separated them, extending through 20° of latitude, Tertiary and Cretaceous rocks were laid down. The West-Indian Islands, by the affinity of their faunas with South-American forms, show that they were formerly connected with that continent rather than with Florida †. The geology of the connecting strip of Central America is not known, excepting that it is partly volcanic. The Gulf of Mexico forms a deep depression, separated from the Pacific Ocean by land, and connected with the Atlantic by comparatively shoal water.

There are 55,000 square miles in the Gulf of Mexico, enclosed by the 2000-fathom contour ‡. This has probably been a post-Cretaceous subsidence, and into it the Mississippi is now pouring the spoils of 1,244,000 of square miles of the North-American continent, its principal contributions being perhaps from the Tertiary and Cretaceous rocks of the West.

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* See "Island of South Georgia," Geol. Mag. 1884, p. 225.

† Alex. Agassiz, "Dredging Operations of the steamer 'Blake' in 1879," Bull. Mus. of Comparative Zoology, p. 299.

‡ J. E. Hilgard, "Basin of the Gulf of Mexico," Am. Journ. of Science vol. xxi. p. 290 (1881).

CHAPTER XXVIII.

TIME REQUIRED FOR MOUNTAIN-BUILDING.

ALL calculations of geological time are necessarily but rough approximations. Geologists and mathematicians view the problem from such very different standpoints, that the results are necessarily very divergent. The conditions of the calculation are very little understood, and the figures are usually worked out from very crude and imperfect data.

Let us try and form some idea of the time which has elapsed since the surface of the Carboniferous rocks of the west was finally eroded, and began to receive sedimentary deposits. We shall have to begin by making several assumptions, any of which may be varied as to quantity, according to the knowledge of the operator.

We may assume, with a reasonable degree of probability, that the land-area supplying the detritus for the new rocks was of about equal extent to the new deposits. Doubtless it fluctuated from time to time, being at one time partially submerged, at another more elevated. Again, I think we may reasonably average the new deposits at two miles thick. The present rate of mechanical denudation from the Mississippi Basin is about 1 foot in 6000 years. If we add the matters removed in solution, I have shown that we must reduce the time to 1 foot in 4500 years *.

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* "Denudation of the Two Americas," Proceedings of the Liverpool Geol. Soc., Session 1885, and Amer. Journ. of Science, 1885, vol. xxix. p. 291.

But of the matter removed in solution a large part—indeed, I am inclined to think, the larger part—gets out into the greater oceans. It is spread over a much larger area than the mechanical deposits are. If, therefore, allowing for greater intensity of action in earlier times, though I am by no means prepared to concede this point, we allow 1 foot of denudation for every 4000 years, we shall have made, considering the nature and configuration of the land-area judging by what remains, a full estimate *.

These data being taken, the calculation is one of simple proportion, the result being that, under such conditions, the deposits from the Carboniferous upwards have taken 42½ million years to accumulate. Under these conditions 42 million years is the minimum time we can allow for deposit alone. But it is highly improbable that such an enormous land-area kept pouring its detritus into one area without intermission for so long a time.

Partial elevation, local unconformity, and fluctuations of the drainage-basins would occur over and over again; and all these take time; but how much? At the best we can but guess; probably it would double the time of deposit, but to be within the mark, let us add one half.

It will doubtless be considered incredible by those who are not in the habit of dealing with the question, that such a length of time elapsed. If we look at the enormous changes that have taken place in the fauna since the commencement of the Triassic period in light of evolution by slow changes, it may not seem so strange. To the time taken up by deposit, we must now add that of mountain-building, volcanicity, and elevation. The data for making this calculation are still more

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* Dr. James Croll, in a very able discussion of "The Methods of Calculating Geological Time" says ('Climate and Cosmology,' p. 276):—"I think we may assume, without the risk of any great error, that the average rate of sub-aërial deundation during past geological ages did not differ much from the present."

imperfect, but to our 60 millions of years we may safely add another 20 millions when we consider the enormous masses raised, the extraordinary denudations that have taken place, the changes of climate, and the long persistence of Quaternary lakes. This will give 80 millions of years from the commencement of the American Triassic to the present time *.

Whether we accept these figures or not, or modify the data and so the result, we shall still arrive at the grand generalization that a mountain-system in building, from its inception to its completion, covers, and necessarily covers, an immense period.

These calculations may be checked by a similar process applied to other great mountain-chains of the same age. For the Andes and the Himalayas we await more complete information.

The Alps would constitute a more difficult problem. Suffice it for our present purpose to give this one illustration.

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* Dr. George Darwin, in his late Address to the Mathematical and Physical Section of the British Association (1886), very fairly discusses the various methods of estimating geological time, in a spirit far removed from the dogmatic assertion indulged in by some physicists. However inadequate the data derived from the ascertained present rate of denudation may be, we must not forget that it *has* been ascertained by observation, whereas the basis of the physico-mathematical methods is *purely* hypothetical.

CHAPTER XXIX.

PERMANENCE OF MOUNTAIN-CHAINS.

From the foregoing considerations it will be seen that mountain-ranges are very permanent structures.

They have been built up by an actual thickening of the crust, and cannot be removed except by denudation. They may, ere they become very old, be broken up by faulting, yet still form prominent features of the Earth's surface. They may be covered up by fresh deposits, and yet part of their prominences remain to attest their site and direction. Not the least interesting of the many geological phenomena of the British Isles are the remains in Scotland, England, Wales, and Ireland of a grand system upheaved in Silurian times. Of these we shall have to speak hereafter more in detail. Can we imagine a more striking testimony to the lasting nature of these monuments of former periods than that there should be not mere shreds and patches left, but solid mountain-blocks ?

Mobility and permanence seem to be strangely combined in the various features of the Earth's surface.

It is clear, from all the evidence of these investigations, that a great mountain-range once formed will remain the water-parting of a continent for untold ages. Fluctuations will doubtless take place again and again in the relative levels of the land, so that the water-shedding may be thrown first this way then that; subsidences may occur forming lakes, inland seas, or gulfs connected with the ocean. The land may increase or diminish in area, river-systems may be flexed, but the strong ridge drawn across a continent by a mountain-range will remain through all these revolutions of time a great divide that the rivers cannot pass. None of the mountain-ranges from the Alleghenies to the Rocky Mountains are breached by great rivers draining a large area beyond. The rivers by which mountains are sometimes breached, as a rule have simply worn themselves backwards through having originally started at a higher level. Rivers frequently run parallel with and between mountain-ridges and ranges for long distances, and then break through them, but rarely or never bisect them. This is true, not only of North America, but of South America, Europe, and Asia, as an examination of accurate maps will show.

The ridging-up of mountain-chains, it is thus seen, map out upon the Earth's surface certain fixed boundaries. These boundaries form permanent drainage-areas, until modified by other upheavals. The upheaval of mountain-chains cannot precede deposition—must, in fact, follow it. We therefore have strongly-marked lines, as it were, chalked out for us by which we can partially unravel the complicated operations of nature. Thus, in the revolutions of the Earth's surface, a drainage-area may be converted into a basin of deposition, while, on the other hand, an area of deposit may be converted into a basin of denudation. These fluctuations may occur again and again, and the materials may be transferred from one area to another many times before sufficient accumulation takes place to affect the internal temperature and excite those tremendous forces which it has been our object to investigate.

Though these fluctuations occur, and leave their marks in the geological record of the rocks, it follows that there is a tendency for the detritus worn from the land to accumulate in definite areas; these areas, finally connected together, form the *loci* of mountain-building. Can we, with these principles in view, take a peep into the future? Let us [illegible]

CHAPTER XXX.

MOUNTAIN-BUILDING IN THE FUTURE.

Elsewhere I have shown[*] that the basin of the Atlantic receives, directly or indirectly, the drainage of 21 millions of square miles of land, more than one third the total land-area of the globe. The largest rivers in the world—the Amazons, La Plata, Orinoco, and Congo—deliver their burdens direct into the deep ocean, and innumerable other rivers bring fringing deposits to the coasts.

From the Arctic Regions, Baffin's Bay, and Labrador stones, sand, mud, and gravel, ice-raft- and iceberg-borne, contribute their quota to make up the West-Atlantic deposits. The Gulf-stream brings up spoils of land from the south. The Mississippi is encroaching on the Gulf of Mexico.

Though a large part of North America was submerged in glacial times, the drainage of the continent has been eastwardly since the upheaval of the Rocky-Mountain system. In South America, since the upheaval of the Andes, the drainage has also been to the eastward.

Though portions of the continents were submerged in Tertiary times and others in post-Tertiary, there has been a travel of material constantly east. We may therefore well ask, Where is the detritus, the accumulation of so many millions of years? Some little of it is on the land in the Amazons valley, in the Mississippi valley, and spread out in the form of glacial and post-glacial deposits over a large extent of North America. But by far the greater bulk is doubtless in the Atlantic basin. Opposite the mouth of the Amazons there is a plateau or bench of deposits, having very shallow soundings from the coast to the eastward margin from which the bottom quickly slopes to the Atlantic deep.

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[*] 'Denudation of the Two Americas,' p. 26.

Over the whole of this wide area there is no rocky bottom. This deposit is but a type of what occurs all along the Atlantic coast of both Americas. It is here, and beyond, in the far deeps, that we must look for the spoils of the present continents. Marginal flexures may have taken place in the Earth's crust, but the Atlantic slope beyond the platforms is probably a slope of deposition. We have seen that the great deposits out of which mountain-chains have been upraised are many miles thick, thicker than the greatest depths of the Atlantic Ocean. Is it not a justifiable speculation that there may exist such geosynclinals in the *locus* of the greatest deposits fringing the Atlantic seaboard of the Americas?

Probably the deposits may extend far out beyond these benches, and through subsidence and increasing depth of water may have ceased to receive such sedimentary additions from the land as formerly. If so, they may be covered up and obscured by a thinner covering of deep-sea ooze.

It is impossible to do more than surmise at these secrets of nature, but that an enormous deposit, worn from the continents of America, is lying in some form in the Atlantic bottom, we may rest assured.

In the far future, when in the course of the revolutions of the Earth these deposits become of sufficient depth and extent, may we not expect a range or ranges of mountains to be ridged up from what are now the depths of the Atlantic? If this process has occurred before at various places and in various periods of the Earth's history, have we not a right to assume the probability of its repetition? The internal forces of the Earth are, we have seen from this investigation, far from being exhausted, and we are a long way from the "dead-planet" period.

We may apply this theory of the permanence of drainage-areas bounded by mountain-ranges, but subject to fluctuations of level and minor revolutions of the surface, to other lands than the American continents. Thus the whole of Siberia drains into the Arctic Ocean, and there seems no valid reason to doubt that it will for ages continue to supply material for deposit in that basin. Great geographical changes may take place, a great part of Siberia might become submerged, or land might stretch out further north. Subsidences ending in lakes or inland seas might occur, but so long as the mountain-chains of Central Asia exist, it seems certain that the travel of materials will continue northwards. In this way a varied geological province is created, and fluctuating conditions within certain limits end in a great well-defined, but varied, basin of deposition. Then comes a great revolution of the Earth's crust, in which these deposits are compressed together, heaved and ridged up, and a new continent formed, partly out of the new lands and partly out of the old.

In this way I conceive the continuity of the land-areas of the world through all geological time has been preserved. I doubt if there has ever been an entire submersal of a large land area so that every living thing upon it has been destroyed. Such catastrophes may happen to islands. Thus, as one part of a continent is destroyed by denudation, another part is added to it by accretion and upheaval.

In this way I conceive the permanence of land areas can be explained. Upheaval being dependent upon previous deposition, the general proportion throughout the world of land areas to water areas is preserved. When we consider the mutations the Earth's surface has undergone, as read in the history of the rocks, and the interdependence of the faunas and floras of the globe through all geological time, we are struck with wonder at the continuity of the organic and inorganic systems. Either we must call in the old explanation of ever recurring creation to keep the Earth whole, or there must be a nice adjustment of recurrent causes acting towards the preservation of the land areas. The first explanation is not admissible in a scientific treatise. If true, the phenomena of nature would need no explanation. It would be alike useless and impious to attempt to fathom any of the mysteries of nature if dependent upon an ever-changing divine will.

If, on the other hand, the preservation of the geological continuity of land areas through all time be the result of deep-seated causes, then it is a fit subject for investigation. This personally I believe to be a diviner and nobler faith, and one for which the reasoning powers and curiosity implanted in us were given.

When we consider that, roughly speaking, the land is only one fourth the area of the whole globe, and the water three fourths, with an average depth of from 2 to 2½ miles, and that a constant interchange has been taking place between them during geological time, we cannot help being impressed with the preservation of things mundane through untold millions of years.

We can calculate almost as a matter of certainty, that if no changes took place except those due to deundation, that within a given time, very much below what has really elapsed, the whole of the land areas would be reduced to sea-level. The early geologists saw this, and also recognized the preservative nature of volcanic action. If we have not utterly failed in our investigation, we have caught a further glimpse of cause and effect in the interdependence of sedimentation and the local development of heat, mechanical force, and volcanic action, which have marked out afresh from land and ocean at various times in the Earth's history well-defined geographical regions.

In this way new lands are born, contiguous to, and in communication with, old land areas, which constantly get broken up and sink beneath the wave.

Thus we may sum up the result of our investigations in the statement, that the permanence of land areas is the permanence of *continuity,* not of location.

We are indebted to Prof. J. D. Dana for some of the earliest views on the development of continental land; the views here sketched out, though somewhat more elastic, are in many ways in substance the same. Dana looks upon the development of continental land as analogous to animal growth, and if the similitude be not pushed too far it aids the understanding *.

These views of continental stability through long periods of time, are not to be construed into an admission that there has been no interchange of land and deep ocean. On the contrary, logically worked out, in the revolutions of time such interchanges must result, but this is a matter of controversy which it is unnecessary here to enter upon.

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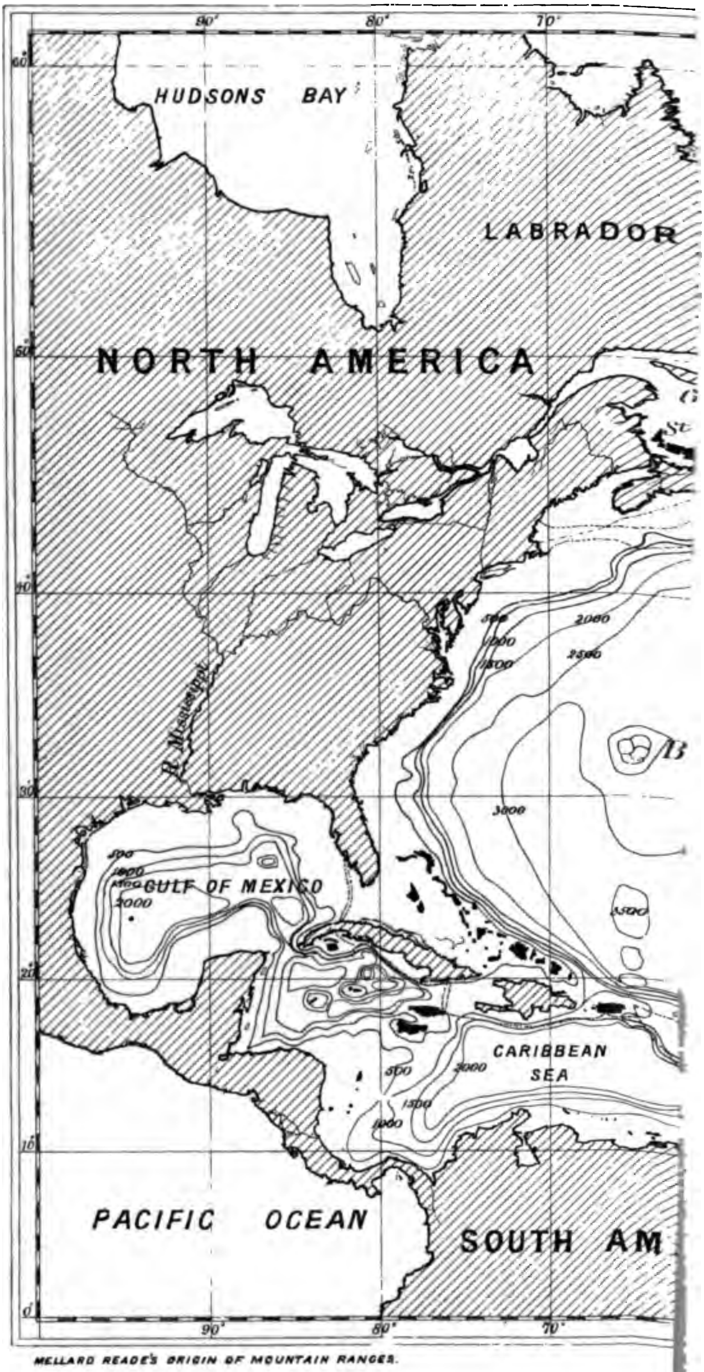
* Dr. R. Owen ('Key to the Geology of the Globe'), Dr. Sterry Hunt, 'Chemical and Geological Essays,' Sir W. Dawson, and many other American geologists seem much impressed with these analogies.



MELLARD READE'S ORIGIN OF MOUNTAIN RANGES.

PLATE XLI.

Contoured Chart of the North-Atlantic Ocean.

In this chart the form of the North-Atlantic Ocean-bottom is approximately indicated by contour-lines 500 fathoms apart vertically. I am indebted to the kindness of Sir James Anderson, the eminent telegraph-engineer for this interesting information. It will be observed that along the western margin of the Atlantic, that is along the eastern coast of North and South America, the continental slope from the 500 fathom contour to the deep ocean is much farther from the coast-line than is the complementary slope on the Spanish and African seaboard, which, until we arrive at the Gulf of Guinea, is close inshore. At the same time the inequalities of the bottom are very much greater on the eastern margin of the North Atlantic than on the western. In laying the telegraph-cables Sir James Anderson informs me that they find very great inequalities in the bottom from Lisbon towards the Canary Islands. Off the Burlings, lat. 39° 35′ 30″, long. 9° 54′ 00″, "the ship had 1300 fathoms under her bow, and sounding under her stern they got 800 fathoms." The valleys are frequent and very precipitous. In contrast with this, the soundings at the mouth of the Amazons for a distance of 60 miles from the coast rarely exceed 10 fathoms, and for 150 miles reach no more than 45 fathoms. I infer from these facts, and from the nature of the bottom, that a levelling-up process is going on. The sediment brought down from the enormous land areas of North and South America extends itself in submarine deltas, from which ocean-currents distribute it widely along the whole coast. It is quite evident, from the grades and depths of the old river-beds, that the continents have subsided considerably. The ancient bed of the Mississippi is over 630 feet below the sea-level, and its grade is lower (as pointed out by Prof. J. W. Spencer) than that of the present river-bed. The soundings and dredgings on the course of the Gulf-Stream as stated by Prof. Verrill, show a sandy or clayey bottom at depths of over 1000 fathoms. It is impossible to give all the evidence here, but it is distinctly in favour of the view borne out by other geological considerations, as pointed out on p. 309, that the western side of the Atlantic is the site of deposits that have been accumulating for millions of years.

As regards the eastern side we have not so much evidence, but Mr. J. Y. Buchanan says ('Nature,' March 25, 1886, p. 495):—"The African rivers are quite stupendous, and have much to do in giving the Gulf of Guinea its peculiar character. The drainage of quite 90 per cent. of the whole continent empties itself into a very restricted area of the sea, the formation and conditions of which it has profoundly modified."

I have discussed these physical questions more fully in the "Denudation of the Two Americas," and "The North Atlantic as a Geological Basin" (Proc. of the Geol. Soc. of Liverpool, Sessions 1884–86).

CHAPTER XXXI.

PHYSICAL AND GEOLOGICAL HISTORY OF THE BRITISH ISLES.

Though Great Britain has contributed so fully to the science of Geology, some of the problems of mountain structure can be investigated under more favourable conditions in other parts of the globe.

The very nature of the country, so admirably adapted for working out the historical relations of the rocks, is from its complex structure not so easy to read dynamically.

We have in the preceding pages traversed some of the most interesting districts of the United States, where, from the age, nature, and extent of the great mountain upheavals, the process of mountain-building can be studied in some aspects to greater advantage than in Britain.

The mountain-ranges in America being on a large scale, and many of them of late date, evidence of certain phases of structural history, here destroyed by denudation, is in America preserved.

On the other hand, when we come back with our ideas enlarged and minds refreshed to the study of this wonderful little island, denudation throws more light upon some of the earlier stages of the process than can be obtained in the United States.

We can here, so to speak, examine the history of a mountain-range at a lower base-level, as the scalpel of denudation has exposed much, especially in North Britain, that in other countries lies concealed.

According to my views, the exposition of which has been attempted in this work, a large part of the British Isles represents the deeply truncated base of a stupendous system of mountains, upheaved out of Cambrian and Silurian sediments * at or towards the close of the Silurian period, the gneissic axis of which lies to the westward of the Scottish coast. So far as we know by exposures in the northwest of Scotland and the Hebrides, together with small exposures in Anglesea and Shropshire, the Malvern Hills, and possibly Charnwood Forest in Leicestershire, the Palæozoic strata rest upon a floor of Archæan rocks. It is due to a small band of enthusiastic workers that these facts have been gradually brought to light, though not without many expressions of dissent.

When the members of the Geological Survey found it impossible to go on mapping the Highland Rocks on the theory and classification not unnaturally adopted by Murchison, and supported for a long time by many eminent geologists, a great and distinct step was taken in advance; an obstructing rampart was broken down. That Murchison's view prevailed so long is not surprising. It was supposed, I believe falsely, to accord better with Lyellian principles of Geology than Prof. Nichol's alternative view. The admission of an Archæan System, or one of equivalent nature, doubtless seemed to these earlier observers a retrogression to the exploded ideas of Werner and the "primitive schists" ridiculed by Hutton.

But wheresoever facts tend, thither we must go, if truth be the object of our search.

On very good evidence those who have most studied the subject pronounce the widely scattered but small areas mentioned to be of Archæan age. It is not my object to enter into any controversy as to the methods of geological

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* I had formed this view before Prof. Lapworth stated the same conclusions with regard to the Highland Rocks. "Secret of the Highlands," Geol. Mag. 1883.

inquiry which have led to these views, but we may well consider a generalization bearing upon the whole question.

Unless we have been altogether mistaken in our views regarding the relations subsisting between sedimentation and plication, the Archæan rocks of the Highlands, now authoritatively admitted into the geological system, are not, in fact cannot be, an isolated phenomenon.

According to the principles here set forth, they must constitute part of a vast system.

The folding, plication, and metamorphism, most of which took place before the deposition of the Palæozoics, could not have been impressed upon the Archæan rocks had they not been part of a grand system of sediments deeply buried at the time of their plication.

It is here that the American examples come to our assistance. Immense areas of Archæan rocks exist on the North-American continent. We have seen that they are strongly developed in the Rocky Mountains, forming the cores of great ranges.

In Canada, where they were first geologically worked out by Sir W. Logan, they occupy most extensive tracts. The reason we see so little of them in Britain is that they only appear where forced up from below, entangled in the Palæozoics, as in North-west Scotland, or forming a floor on which the Palæozoics rest, or as the cores of mountains like the Wrekin*.

If this reasoning be valid, these Archæan areas are most probably connected, excepting where their place is taken by granite or other igneous rocks. Upon this floor a great thickness of Cambrian and Silurian rocks was laid down, reaching in all some 35,000 or 45,000 feet †. During the deposition of the Lower Silurians, volcanic action was energetic in North Wales, and great thicknesses of interbedded ashes occur among the sediments. That this volcanism was not the cause of the upheaval of the Snowdonian mountains, is shown by the interbedded ashes being involved in the folding which occurred towards the close of the Silurian epoch (see fig. 3, Plate XIV. p. 98). At the time the marine sediments of Snowdon with their intercalated ash-beds were being laid down subaerial volcanoes existed in the North-west of England *.

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* Callaway, "The Pre-Cambrian Rocks of Shropshire," Q. J. G. S. Nov. 1879.

† Hicks, Q. J. G. S. 1875, p. 552; Geol. Mag. 1876, p. 156.

That these Cambro-Silurian deposits were of enormous extent as well as thickness, occupying a long period of geological time in their accumulation, we infer not merely from their general distribution over the British Isles, but from the fact that wherever found the strike of the rocks is usually in the same north-easterly direction. Here we have the advantage of our generalization of the dependence of mountain-building on previous sedimentation in aiding us to a clearer view. Persistent strike means force acting over a great area, while the great disturbance, folding, overfolding, the superposition of older strata upon newer, the flowing of deeply buried rocks, together with reversed faulting and fracture, show, as we have seen from every example quoted (though the illustrations are world wide), that the sedimentation was of enormous extent. Our horizon is therefore not bounded by the British Isles; we see plainly that the forces which produced this lateral compression of the rocks were called into being by the sedimentation itself.

We have seen that the forces active during the period of volcanicity in Wales, whatever may have happened at greater depths, did not fold or laterally distort the deposits then being laid down. It was only when the vents became sealed up by an enormous deposit of Upper Silurians that the pent-up and

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* "Geology of the Northern part of the English Lake District." Mem. Geol. Surv. (1876), by Clifton Ward.

growing forces developed by rising heat acted upon the overlying mass of rocks by cubical and lateral expansion. The amount of mountain-building and lateral disturbance of the strata is proportionate to the resistance to be overcome. The very deposits, the weight of which causes the resistance, call into being, or rather excite, the forces that overcome them, namely volumetrical and horizontal expansion by heat.

This development of energy was accompanied by further volcanic action, as shown by the pipes and dykes of trappean rocks that penetrate the strata, as well as by the bosses of porphyritic felstóne which are a feature in North Wales.

The behaviour of the rocks under the increasing lateral compression differed accôrding to their thickness and internal strength. The massive beds in North Wales bent under the strain into great anticlinals and synclinals with sweeping curves, while the areas of more thinly bedded rocks were more acutely bent, folded, and tightly compressed.

But it was in the North of Scotland that the subterranean forces made the most terrific display. Here the Archæan floor was forced up in great tongues and loops, extending and lengthening the Palæozoic strata above by detrusive compression. Under the combined influence of the uplifting masses below, and the lateral advance of the overlying strata from the flanks, the old and new rocks became inextricably entangled. They were over-folded, over-faulted, and even in one case, according to the geological surveyors, pushed 10 miles one over the other, so as to deceive even the experienced geological eye into a false appearance of geological succession.

As we have seen, though the forces concerned in these great movements were mainly acting from the North-west and South-east, there was really a compressive movement acting centripetally, as shown by many examples given of the domical form of the anticlinals, and the elongated basin shape of the synclinals. The probability is that the major axis of the area of Cambro-Silurian deposit was approximately in the direction of the major axis of the ellipsoïdal anticlinals or domes, that is in the direction of the strike of the rocks.

At or towards the close of these great upheavals, lasting eras of geological time, the Old Red Sandstone was deposited.

We have seen how in Western America during the upheaval commencing towards the close of the Cretaceous period, and ending in the Rocky-Mountain, Plateau, and Great Basin Systems, great denudations took place accompanied by the deposition of immense thicknesses of Tertiary strata, both freshwater and marine. I take it that the Old Red and Devonians of Great Britain represent a somewhat similar succession of events—great inland seas, freshwater lakes, and contemporaneous marine deposition.

It was, as Sir Andrew Ramsay clearly shows, a continental period *.

Again, there was an exhibition of volcanic energy on a large scale ending in subsidence and the marine conditions of the Carboniferous Limestone.

The Carboniferous period appears to have been ushered in by distinctly sea conditions, as shown by the enormous development of Carboniferous Limestone in Derbyshire, the North of England, the Mendips, and a large part of the area of Ireland. In Scotland the deposit is represented by the Calciferous Sandstone. It is not alone by the actual bulk of what is left that the extent of these deposits must be judged, but also by the remnants exceptionally preserved from widespread denudation.

To Prof. Judd's researches we are indebted for a more distinct knowledge of this fact. He was the first to thoroughly grasp the idea that most of the greater divisions of the later geological series had a much wider extension in Great Britain than the evidence at first appeared to warrant.

After the sea conditions, the shallow-water and coal conditions came in, and many thousands of feet of alternating

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* 'Physical Geology and Geography of Great Britain.'

sandstones, grits, shales, and coal-beds were laid down in particular areas. From the very nature of these deposits it follows that they could not be so widespread as those laid down in sea-beds. The conditions were principally estuarine, and the detritus must have been worn off some great continent. One of the most striking facts of Geology is the almost exact parallelism of the coal-bearing strata in Nova Scotia with that in England, and it would seem to point to a community of origin. Whether they were derived from one continent, which seems not improbable, or whether similar conditions prevailed on the two sides of the Atlantic at the same period, which seems less likely, it constitutes one of the most salient facts in stratigraphical geology *.

During and after the deposition of these great contemporaneous formations there were displays of volcanic energy; but only after the deposition of thousands of feet of rocks over thousands of square miles did mountain-building again begin. We see the result of upheaval, lateral expansion, and consequent folding in the Pennine Chain, in the Mendips, in the great mountain-masses of Benbulben and the Burren in the West of Ireland, and in Scotland in the folding of the Carboniferous rocks in the basin of the Firths of Forth and Clyde.

Here, again, as I have pointed out, the anticlinals take an elongated or boat-like domical form, which, together with the normal form of coal-basins, shows that the pressure has been

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* Sir Charles Lyell has dwelt upon this fact, and more recently Prof. Hull has discussed it in his able paper, "On the Geological Age of the North Atlantic," also in a letter to 'Nature,' Sept. 23, 1886, p. 496. Sir William Dawson, in his Presidential Address to the British Association, points out that the Carboniferous strata extended eastward from America into the Atlantic. The question of "how far" into the Atlantic has not been settled, and will probably remain an open one for some time, each geologist deciding according to his particular bias, the evidence not being of a nature sufficiently conclusive to bring about a general agreement.

centripetal. The directions of the axes of upheaval have not the parallelism that distinguishes the Cambro-Silurians; there was not that preceding uniformity of deposition, nor were the British deposits of anything like the same importance, excepting commercially, as those of the preceding periods.

I have already alluded to Prof. Judd's discovery of Carboniferous strata in the Highlands of Scotland preserved by a basalt capping and by being dropped down at least 2000 feet between other strata by faulting *.

Even if we had not these evidences for our guidance, we might conclude that the Carboniferous formation originally extended far beyond its present boundaries in Scotland. The central coal-field of Scotland is preserved in precisely the same way by being dropped down bodily between great faults having a direction approximately parallel to the general strike of the underlying Silurians.

It is clear that this is a downthrow, and it follows as a matter of stratigraphical demonstration that the Carboniferous area must be only part of a vast sheet of similar deposits that overspread probably the larger part of Scotland. This is, I consider, a great example of contraction faulting, and cannot reasonably be explained by upheaval. Indeed most of the faults in the Carboniferous strata that I have seen in the British Isles are in my view normal or contraction faults. They are in such cases later than the foldings accompanying the mountain upheavals.

This continental period was accompanied again by the phenomena that followed the Silurian upheaval. Great inland seas and freshwater lakes, in which the Permian beds of the Vale of Eden, and the Triassic beds, so strongly developed in Cheshire and Lancashire, were laid down, remains of the Triassic being also strangely preserved by

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* Address Geol. Sect. British Assoc. 1885, p. 13 of reprint.

faulting in County Louth, Ireland, and even among the Old Red Sandstone of Elgin, Scotland.

It is evident that here, again, we have only the remnant of a great formation, the lithological similarity of which over extensive areas is a striking proof of unity of origin. Prof. Judd points out that the Trias of Scandinavia, consisting of variegated sandstones and conglomerates containing much calcareous material, is absolutely undistinguishable from that of the Western Highlands.

To this recurrent land-period succeeded the estuarine and marine conditions of the Rhætic and Infra-Lias formations, thinly developed in England, but reaching in the Highland districts a grand development and great thickness, and containing thin seams of coal.

Estuarine and marine conditions continued throughout the whole Jurassic period, as attested by the prevalence of Ferns, Cycads, and Conifers, with alternations of marine forms of life.

In the Upper Jurassic of Sutherland, not less than 1000 feet thick, are found evidences of mighty rivers, the banks of which were dotted with tree-ferns, cycads, and gigantic pines *.

Again a period of elevation and land conditions set in, represented by the Neocomian, in which no traces of marine deposits occur. Enormous denudation again followed the upheaval and preceded the Cretaceous epoch.

It is probably in this period that most of the disturbance, flexing, and faulting of the Triassic beds occurred. The Cretaceous formation is found resting in turn upon every member of the Jurassic, the Rhætic, and the Trias, and all the different Palæozoic and Archæan rocks, thus attesting the energy and endurance of the subaerial agencies. To this period also belongs the Wealden, so that the conditions usually following upheavals again recurred.

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* Ibid. p. 14.

The Cretaceous, represented in England mainly by the Chalk, and variously considered by eminent geologists, according to their speculative bias, as of deep oceanic or of shallow sea origin, now succeeded.

The period of time represented by these calcareous deposits must be enormous, and whatever the depth of water was in which they were deposited, the conditions were entirely different to any that had preceded them in the British area.

After these widespread and probably oceanic deposits had accumulated through untold æons of Geological time, continental elevation occurred. Subaerial waste followed elevation, and the period of terrestrial conditions must have been proportional to the time of previous deposition. At all events it is considered that the greatest known palæontological break occurs between the Cretaceous and the Tertiary. The elevation in Britain was accompanied mostly by gentle flexuring of the strata and by faulting.

We have seen that this period was in America one of great mountain-building, which has continued almost to the present day. The amount of sediment and calcareous matter which covered the sea-floor of Britain, though representing an enormous lapse of time, was small in thickness compared with the American Cretaceous: hence, as surely as effect follows cause, the compression, bending, upheaval, and general disturbance of the strata was proportionately less.

No mountain-range was developed, only low domical anticlinals like that of the Weald.

The Tertiary now succeeded, and very little sedimentary and stratified deposits of this period occur in the British Isles. It was in the North of Ireland and the West of Scotland essentially an age of volcanoes and the outflow of vast sheets of basalt. Prof. Judd has so ably developed this part of the subject that little is left for others to say. To the volcanic outflows, as he shows, we owe the preservation of many interesting vestiges of a bygone era. Great volcanoes were built up, immense floods of lava deluged the country. The rocks were riven by dykes ramifying over a large area. Unfortunately we are at present unable to tell what effect these subterranean forces had upon the ground outside of the area to which the remains of the igneous outflows are now confined.

We know that during this period no great mountain-range was built up in Britain; there were no sufficiently great masses of sedimentary deposits for the subterranean forces to act upon.

It is certainly remarkable that both in Britain and far-off Western America, though the conditions of equivalent deposits were so dissimilar, the same order and succession of events, broadly speaking, followed.

The upheaval began in the Cretaceous in both areas, and terrestrial conditions more or less persisted to the present time, broken here by what is called the great glacial submergence. It appears to have been a time of denudation for both countries. To this fact is due no doubt the destruction in the North-west of England of all the beds from the Cretaceous down to the New Red Sandstone, and also a large part of the latter. That these formations, and it may be representatives of the Tertiaries, formerly covered this deeply denuded country there can be little doubt.

The outliers of Lias in part attest this, and also the general distribution of the Oolitic and Cretaceous rocks. They have most probably been worn back by atmospheric agencies from the Irish Sea eastward to the Oolitic escarpment traversing England from the South-west into Yorkshire.

This is but a very slight outline sketch of the physical and geological history of the British Isles, but it has been sufficient to bring before us the normal order and succession of geological events with considerable clearness.

Shortly stated they are as follows:—First, great accumulations of marine deposits accompanied by subsidence. Second, upheaval of the sediments, folding, flexing, long continued terrestrial conditions, and great denudations, accompanied by the deposition of sediment in freshwater lakes or river valleys. Third, subsidence followed by estuarine alternating with marine sedimentary deposition, and then by purely marine conditions. Fourth, the accumulation of littoral sediments in great areal masses. Fifth, alternating estuarine and marine deposition. Sixth, upheaval, folding, flexure, and a recurrence, with variations, of this succession of events.

Such is the geological cycle of recurrent periods. No two periods are precisely alike, and the geological record in any particular area is not always perfect. We have seen from geological history that the succession of deposits usually follows in this order; and we have I hope by this time been able to satisfy ourselves why such a succession must result from the natural conditions of geological change which it has been the object of this treatise to investigate. It is a very interesting and striking fact that we should in this little isle of ours possess such a complete series of geological records, none the less complete that they need interpreting by the aid of the geological history of adjoining or distant provinces.

We have found in the progress of these investigations that the key to geological difficulties must often be sought elsewhere. It is thus by studying the work of geologists of all countries, comparing and uniting the observations and views of various minds working under different conditions and with perhaps different standards of measurement, but withal possessed of a central desire to get at the heart and truth of things, that the great cause of geological science is best advanced.

CHAPTER XXXII.

OUTLINE OF THE THEORY OF THE ORIGIN OF MOUNTAIN-RANGES BY SEDIMENTATION ACCOMPANIED BY LOCAL CHANGES OF TEMPERATURE IN THE EARTH'S CRUST.

MOUNTAIN-RANGES are ridgings up of the Earth's crust which take place only in areas of great sedimentation.

The exciting cause of the various horizontal and vertical strains ending in the birth of a mountain-range, is the rise of the isogeotherms and consequent increase of temperature of the new sedimentaries, and that portion of the old crust that they overlie.

This rise of the isogeotherms, the direct result of sedimentation, by a series of reactions described in detail in the body of this work, evidently produces an accumulated temperature much in excess of its normal effect.

The rise of temperature exerts a tendency to expand the new sedimentaries in every direction, in proportion to their extent and mass. The tendency to expand horizontally is checked by the mass of the Earth's crust bounding the locally heated area. The expanding mass is therefore forced to expend its energies within itself; hence arise those foldings of lengthening strata, repacking of beds, reversed faults, ridging up, and elevatory movements which occur in varied forms, according to the conditions present in each case.

The upper layers of the Earth's crust being less and less affected by these variations in temperature as the surface is neared, are by the ridging-up thrown into a state of tension, while the lower beds of the sedimentaries are in a state of energetic compression. The mean rise of temperature of the whole sedimentary mass is half the total rise of the lowest beds.

The old crust and old sedimentaries forming the floor on which the new deposits were laid down are to a considerable depth, which cannot be accurately predicated, equally affected by the rise of temperature; that is, the rise of temperature of the upper bed or old floor means an equal rise of temperature of the whole mass down to what I have called the isogeotherm of fusion, or 3000° F.

The cubical expansion of this second mass is greater than that of the overlying sedimentaries. Old, previously plicated, faulted, and eroded strata are driven together into new bendings and convolutions. Below a certain depth—" the zone of flowing " as I have called it, which varies with the nature and strength of the rock—a new mechanical element comes into play. In place of repacking by folding, the rock under the enormous pressure produced by expansion, which cannot be satisfied horizontally, *flows* along the lines of least resistance. These lines are situated along the axes of anticlinals, which the flowing rock in uplifting extends by what I have called COMPRESSIVE EXTENSION. In this way the gneissic axial cores distinguishing most great mountain-ranges are squeezed up, the sedimentaries being frequently involved and nipped between the expanding anticlinal tongues. Similarly fan-structure is developed together with all the varied forms which axial mountain-cores assume.

The cubical expansion of the mass being driven to expend itself along these mountain axes, an actual transference of material takes place, which gives permanence to mountain forms.

It is also this peculiar development of subterranean force which in great upheavals almost invariably brings up the Archæan rocks as protrusions among the newer rocks, they being eventually laid bare to our view by denudation.

From the time of gestation to the complete growth of a mountain-range, which covers an immense period of geological history, constant variations in temperature are taking place in the subterranean mass; each rise of temperature, however small, marks an expansion and increment of growth, and it is the accumulated effect of these successive efforts which we see in the total result.

Strata are not lengthened continuously, but by small increments, or expansion-creeps.

According to the conditions present, so will be the effect of cubical expansion. Both horizontal foldings and vertical uplifts are expressions of the same force. The form the mechanical effect will assume is dependent upon the plasticity or rigidity of the materials of the Earth's crust acted upon; hence from modifications of the same force may arise the parallel folds of the Appalachians or the Jura Mountains, the gneissic tongues of the Central Alps or the North-western Highlands of Scotland, the Uinta form of simple anticlinal, the monoclinal plateaus of Utah, or the great Merionethshire dome.

NORMAL FAULTING is the result of contraction, and is usually posterior to the folding. It results from the previously expanded rocks returning to their original volume. Hence a normal fault is necessarily a downthrow; for in shrinking to their original volume, from the necessity that the crust should be solid, unequal subsidences occur. Above the zone of flowing the strata shear into wedge-like forms and key up the contraction-interspaces by subsidence, which takes place to the larger extent in the blocks that possess the smaller bases. It is from this cause that normal faults usually hade to the downthrow.

Below the zone of flowing, the rocks, while shearing, close up the fissures by compressive extension, thus adding to the general subsidence of the surface.

It is thus apparent that all the phenomena of mountain-building are the result of local variations in temperature of the Earth's crust, caused by the reaction of surface influences on the heated interior. Every rise of temperature, whatever its amount, in the locus of a mountain-chain tends to elevation and permanent ridging up by a lateral displacement of materials. Every fall of temperature produces a proportionate vertical subsidence of the surface over the district affected; but as the materials laterally ridged up in mountain-ranges by expansion cannot be drawn back again during contraction, there remains a permanent total of uplift in the range with every rise of temperature, that can only be removed by atmospheric denudation. In this way mountain-ranges become permanent features on the Earth's surface, notwithstanding the vicissitudes of the larger areal subsidences and elevations that take place, and the subsidences due to faulting.

During the enormous periods of time consumed in the building of a mountain-range after elevation has begun, an almost infinite number of local changes of temperature must occur. However small these changes may be, they all work towards the same end. Thus ten changes of ten degrees each would nearly equal in total effect a change of one hundred degrees. We have seen in the case of metal sheets that, although on contraction they almost recover their original form, repeated small changes produce rapid distortion. How much more so must this be the case with the Earth's crust, the materials of which possess less tensile strength, while their weight is by comparison infinitely great. None of the material of the Earth laterally displaced by expansion can be drawn back by tension, as is the case with metal plates; consequently the elevation is more rapid and effective.

Further, we have impressed upon us the great fact again and again brought out by geological study, namely, the important accumulated effects wrought in nature by small recurrent causes. When we view a mountain massif, like that of

Mont Blanc, it may be difficult to realize that the recurrent forces of expansion could have built up so imposing a structure. It is, however, in relation to ourselves that it appears such a tremendous mass; compared with even a small portion of the Earth's crust, from which it is derived, it is a mere nothing; while the whole of the mountain-ranges of the Earth, as is often pointed out, are almost imperceptible excrescences on the surface of the globe, considered as a plane on which they stand.

Again, when we find that ordinary atmospheric changes produce such remarkable contortions in metal exposed to their influence, it would be strange indeed did not the greater, though slower, changes which take place in the Earth's crust in connection with sedimentation produce upon it an equivalent effect. It seems remarkable that this should not earlier have been perceived. The changes of temperature have been fully recognized, but their effect on the Earth's crust has been but partially apprehended.

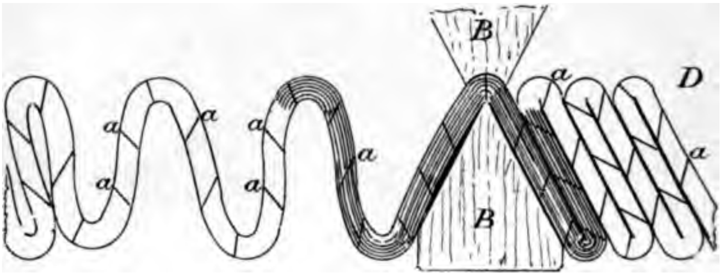


Fig. 2.

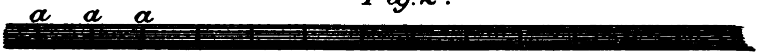


Fig. 1.

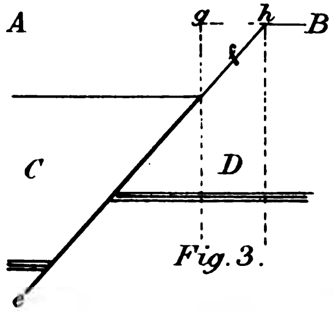


Fig. 3.

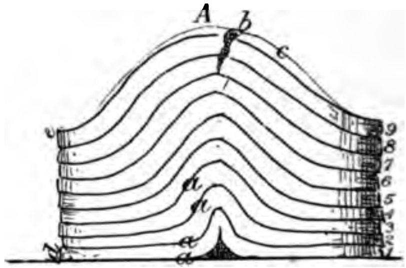


Fig. 4.

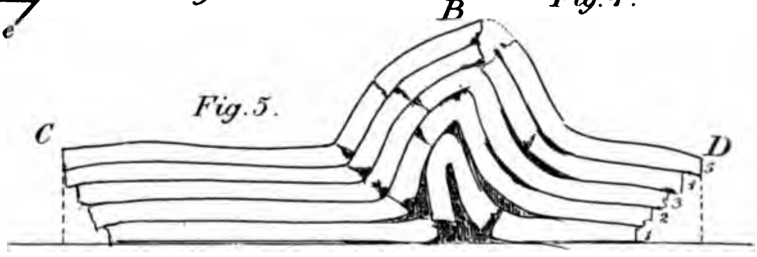
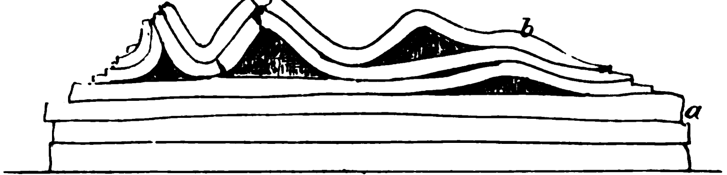


Fig. 5.

Fig. 6.



Scale to Figs 4 5&6.

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PLATE XLII.

Figs. 1 & 2. Experimental illustrations of the sliding of beds upon each other through anticlinal and synclinal folding. Fig. 1 represents the edges of a series of strips of paper; *a, a, a* are parallel lines ruled upon the edges, the paper being compressed while this is being done. Fig. 2 represents the combined strips, part of which is shown in fig. 1, bent into folds. B B are pieces of wood tightly gripping the paper strips at *b*, and nailed to the board against which the strips are folded. From C to B the combined strips are bent into open folds, from D to B into closely appressed folds. The strips are kept in place by French nails driven into the board.

It is seen that the lines *a, a, a*, previously parallel and at right angles to the strips, are now at all angles to the strips and to each other, showing that the individual strips of paper have moved on each other during, and in consequence of, the folding. (See p. 210.)

Fig. 3. Diagram to illustrate the improbability of normal faulting having a considerable hade, being the result of uplifting.

Let A B represent faulted strata and *e f* the inclined throw; then if the block D be uplifted, the rocks on one side or the other must move horizontally through the distance between the vertical lines *g h*, that is they must be compressed or folded to that extent. It is contended that the additional force brought to bear upon the block D, in consequence of its base being larger than the base of the block C, will be insufficient to produce this lateral compression, as less force would be expended in lifting both blocks *pari passu* than in wedging the strata on either side of the fault into a less horizontal space. (See p. 240.)

Figs. 4, 5, & 6. Experimental illustrations of the movements of bedded rocks in folding, by varied applications of lateral pressure.

The apparatus consisted of a wooden trough open at the ends, into which were fitted two sliding compressing bands, each formed of a strip of zinc bent round in horseshoe form and overlapping each other in the middle. The compression-chamber or contortion-box was then filled with the material to be acted upon, which in figs. 4, 5, and 6 were layers of a fine tenacious clay. The pressure was applied with a cramp against blocks of wood sliding in the wooden trough and acting on the zinc bands. The layers of clay were free to move vertically. I am indebted to the Rev. F. F. Grensted, M.A., for aid in the construction of this apparatus, and to the assistance of my sons in carrying out the experiments.

Fig. 4. In this experiment layers of clay, represented by numbers 1 to 9, were placed in the contortion-box. Between each of the layers were fitted two pieces of calico, *a, a, a,* to prevent the beds adhering together. The zinc chamber in this case had rounded ends. On pressure being applied, the beds rose up in the anticlinal A, which fractured at *b*, as shown. The clay in this experiment was a little softer than in experiments figs. 5 & 6. It will be observed that the anticlinals increase in size from the bottom layer upwards, until the maximum is reached at the surface, precisely as previously worked out theoretically in Plate XVII. fig. 4, p. 117.

In consequence of the ends of the compression-chamber being rounded, the pressure as the rounded ends approached each other became slightly converging, the result being that in cross section the layers are a little convex (as shown by the line *c*) like a truncated dome. The size of the finished block is now 6 inches long by 4¼ high by 2½ inches wide. The thickness at *d e* is a little more than the original thickness of the pile. Each layer can be removed so as to show the form of the under layer, as the calico-partings prevent the layers adhering.

Fig. 5. This experiment was made with stronger and thicker layers of clay, five in all, well greased on the surfaces to allow of sliding taking place. Stepped blocks of wood were placed in the compression-chamber, so that the ends of the series of clay-layers being cut square, the compression acted first on the bottom layers and so on upwards. In consequence of the zinc plates gripping the sides of the layers, the whole was at the same time pressed bodily together, though the bottom layers were the most compressed, as shown.

The anticlinal, B, did not begin to rise until a good many turns of the screw had been put on. When once it began, the rise was rapid. The result is seen in the diagram, which is accurately drawn to scale. The anticlinal fractured at the apex, as shown.

In consequence of the compression applied being greater at layer No. 1 than at the surface-layer No. 5, the core of the anticlinal is better developed than in fig. 4. This experiment represents what takes place in nature in a series of beds below the surface, where all the layers expand, but the bottom one expands the most, according to the theory expounded in this work.

The length of the block before compression was 13½ inches; after compression it measured 11⅝ inches from C to D, and 14½ inches over the surface of the anticlinal. The upper layer was thus shortened horizontally to the extent of ·1⅞ inch, and *lengthened* 1 inch measured over the anticlinal; thus illustrating the principle explained in pp. 167–174.

In one experiment I made of a similar nature the original length of the clay series was 9 inches. After compression, the top layer measured horizontally 8¾ inches, and over the anticlinal 9¾ inches, the fracture at the apex being considerable.

Fig. 6. In this experiment the stepped blocks were reversed, so that the greatest compression came upon the top layers, the layers being greased as before; the result, as shown, was a series of anticlinal bends with cavities between them and the under layers. If a compression were produced in the crust of the Earth by it following a shrinking nucleus, and the layer *a* represented the neutral zone between the shell of compression and the shell of contraction (see Plate XVIII. p. 123), and the top of layer *b* represented the surface of the Earth, the foldings that would take place (as explained in Chapter XI. pp. 121–126) would assume the form they have done in this experiment.

I leave the reader to decide whether of these examples of folding, No. 5 is not the most like Nature.

I may add that these experiments are selected out of a number made, and that I have succeeded in producing two overturn anticlinals with a closely appressed synclinal between them. In all cases the apices fractured; the top layer, except in the case of very soft clay, after compression measuring over the sinuosities more than it did before the pressure was applied.

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